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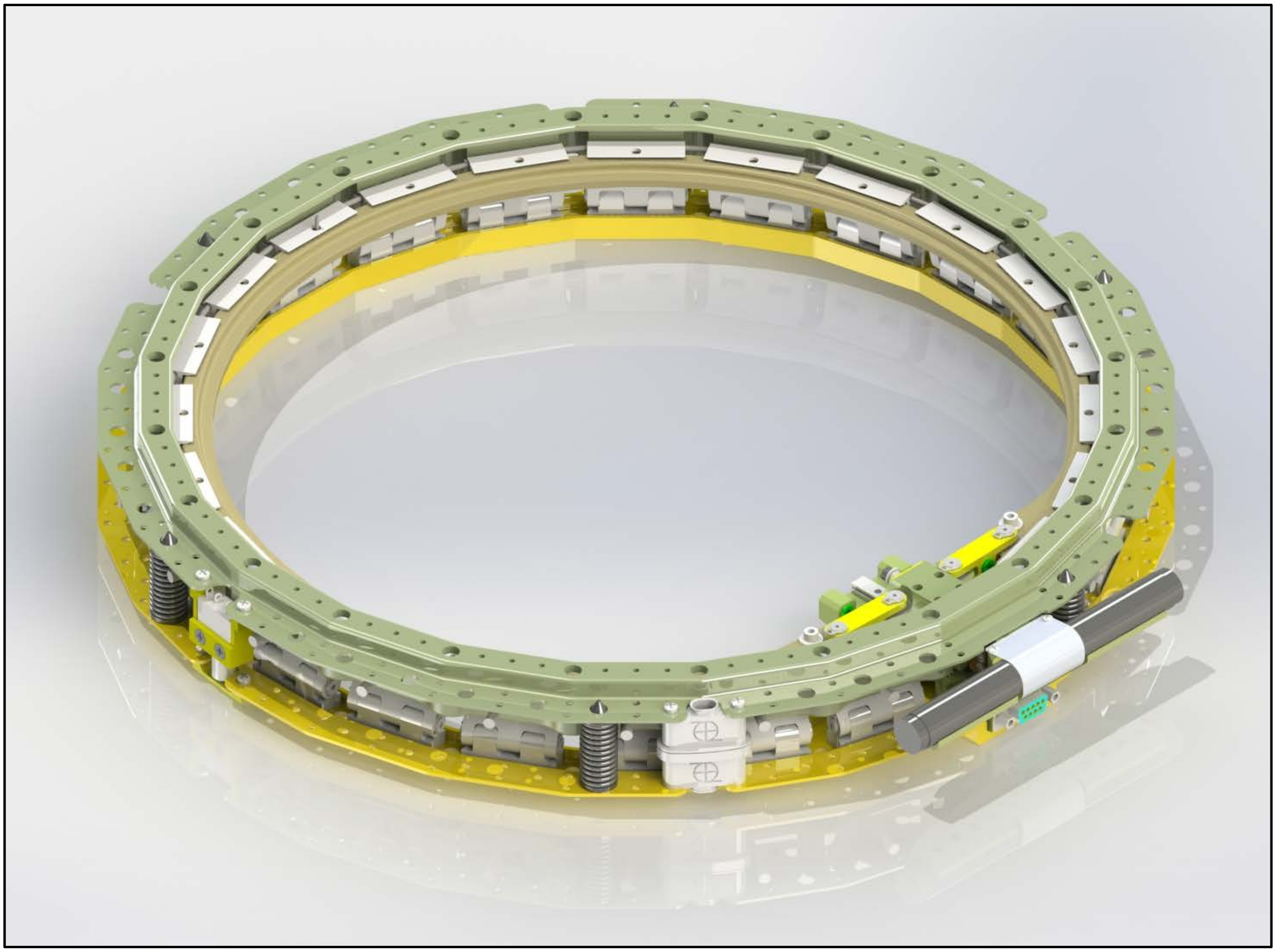
2000785F MkII MLB User Manual

NOTE: To avoid costly test failures and program delays, all users should completely understand this document before procurement and use of the Lightband for any purpose.

Customers are prohibited from operating the Lightband without reading this manual and completing the Lightband Training Course offered by PSC.



US Patents: 6,227,493; 6,343,770; 6,390,416

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1. Revision History

<table>
<tr><th>Rev.</th><th>Issued</th><th>Written By</th><th>Released By</th><th>Change Description</th></tr>
<tr><td colspan="5">Previous revision change logs recorded on file for document simplicity.</td></tr>
<tr><td>D</td><td>02-Apr-13</td><td>AZ</td><td>WH</td><td>• Added Section 9.2.
• Added footnotes to cite source of nominal operation profiles.
• Corrected Equation 5: first ‘m’ changed to ‘n.’
• Normalized data in Table 6-2. Data disclaimer added in Section 6.7.
• Corrected Equation 2.
• Added Figure 6-18.
• Modified Table 5-1 to include flatness for both stiff and flexible structures.
• Corrected Equation 8.
• Corrected caption in Table 6-3.
• Removed flight heritage Table 4-1 and replaced with a reference to PSC’s website.
• Added Section 19 regarding previous qualification testing.
• Added Table 6-4 to Section 6.8.
• Updated Figure 18-9.</td></tr>
<tr><td>E</td><td>10-Jul-14</td><td>AZ</td><td>WH</td><td>• Figure 2-1: Updated.
• Figure 2-8: Added.
• Section 4: Updated flight history quantity.
• Table 5-1: Added row for max. qty. of LCTs, edited row title for max. sum of Connectors, Switches, and Roll Brackets.
• Figure 6-5: Updated with better image quality graphic.
• Figure 6-10: Updated with better image quality graphic.
• Table 6-8: Updated and marked some part numbers proprietary.
• Table 6-9: Added Lightband Compression Tool Assembly.
• Section 6.9: Changed specified torque value, clarified torque exceedances.
• Section 6.9: Added discussion of reduced head diameter fasteners.
• Figure 6-25: Updated.
• Section 6.3 (formerly): Deleted because it was superseded by Section 7.10.
• Figure 7-2: Updated to graphic from 4000697B.
• Section 8.3: Added absorptivity and emissivity ranges for hard anodize.
• Figure 9-5: Added a legend.
• Section 10: Added step 15.1.14 and Table 15-2.
• Section 10: Added comment regarding not-for-flight marking on EDUs in step 15.1.14.
• Figure 15-1: Updated to reflect current standard tests and number of seps.
• Figure 17-2: Added.
• Table 18-1: Changed number of TVac separations from 1 to 2.
• Figure 18-1: Updated with more recent test photo.
• Figure 18-4: Updated with more recent test photo.
• Section 18.1.2: Updated with latest test standards.
• Section 18.1.3: Updated with latest test standards.
• Figure 18-2: Updated.
• Figure 18-9: Updated.
• Figure 18-16: Added.
• Section 20: Updated with latest procedure from 2001066B.
• Section 21: Added reference to document 2002653.
• Section 22: Added reduced-head diameter fasteners.
• Section 23: Added.
• Table 24-1: Updated photo of hex standoff.
• Table 24-1: Added row regarding customer unpacking.</td></tr>
<tr><td>F</td><td>30-Jul-15</td><td>AZ</td><td>WH</td><td>• General: changed order of sections.
• Cover Page: Updated graphic.
• Section 2: Removed PSC Team photo. Removed old photos.
• Section 3: Added item regarding ISS.
• Section 4: Added list of launch vehicles.
• Section 6.4: Corrected initiation time.
• Section 6.6: Added additional explanation, consolidated stiffness figures.
• Section 6.15: Changed title. Combined with section on Refurbishment. Updated energy values to stow and deploy.
• Section 6.16: Corrected gage pin diameter from 0.275 to 0.281.
• Section 6.19: Corrected Sep Switch Data Sheet number typo.
• Section 7.6: Removed Lightband nominal electrical profiles section, removed measurement schematic, and added reference to 2000781.
• Section 8.2: Improved clarity, added table to present data.
• Section 9: Consolidated figures, added tables to present data.
• Section 10: Updated cumulative Lightband operations total, corrected stow energy value, changed monitoring reference from a figure to Operating procedure.
• Section 12 Updated for clarity and added subsections.</td></tr>
</table>

				• Section 12.3: Clarified Viton shedding area to be square inches. Added moly to lubricant mixture call-out. • Section 13: Updated and added specific storage life value. • Section 15.1: Updated with shorter schedule and MLB15 info. • Section 17: Added mention of inventory management software. • Section 18: Removed optional use of Load Cell Link during testing, updated testing standards, updated number of typical operations. • Section 18.1.3: Added discussion of analytical in-flight predictions. • Section 18.2.1: Changed Criterion 1 conjunction from “and” to “or.” Clarified that MOS is on yield, not ultimate. • Section 18.2.1: Added sine burst test option. • Section 18.2.2: Removed “measure generated shock” from test objective. • Section 19: Simplified section figures and data. • Section 19.1: Removed MLB38 qual vibe test info. • Section 20: Removed delaminated staking example, added “accessible” to step 4. • Section 21: Consolidated subsection on wiring harness design into Section 7.3. • Section 23: Added training content and training expiration duration. • Section 24: Updated IAW latest practices. • Figure 2-1: Updated flight heritage values. • Figure 6-12: Updated with latest revision of MBA. • Figure 6-13 through Figure 6-15: Updated with latest revision of MBA. • Figure 6-20: Updated. • Figure 6-32: Updated to reflect realistic Separation Spring quantities. • Figure 7-9: Updated to latest version of profile display program. • Figure 9-2: Added. • Figure 9-3: Updated for clarity. • Figure 9-4: Updated plot with improved formatting. • Figure 9-5: Updated plot with improved formatting. • Figure 15-1: Updated with latest PSC processes. • Figure 18-9: Updated. • Figure 18-11: Updated to remove MMI measurement, changed inputs. • Figure 18-12: Updated image. • Figure 18-13: Added. • Table 5-1: Updated values, changed format, increased max loads, moved location. • Table 6-10: Corrected stored energy values. • Table 9-1: Added. • Table 10-2: Updated quantity of Lightband operations before delivery. • Table 15-1: Added. • Table 18-2: Added. • Table 22-1: Added that LCTs can be purchased.

2. Introduction

The Lightband is a space vehicle separation system. It is used to separate space vehicles from launch vehicles and to separate elements of launch vehicles. The Lightband is offered in a range of sizes from 8 to 38 inch bolt circle diameter.

The content of this user manual is based on the experience of providing more than 100 separation systems to commercial, government and university customers, both domestic and international, whom launch payloads on a broad range of orbital and sub-orbital launch vehicles. The Lightband is a patented, Commercial Off-The-Shelf (COTS) technology. It is made with materials and methods consistent with high-reliability and Class-A space flight hardware.

This is the user manual for the Mark II Motorized Lightband only. **The MkII can be uniquely identified from other Lightbands. On the MkII, the motors are on the outer diameter of the unit.**

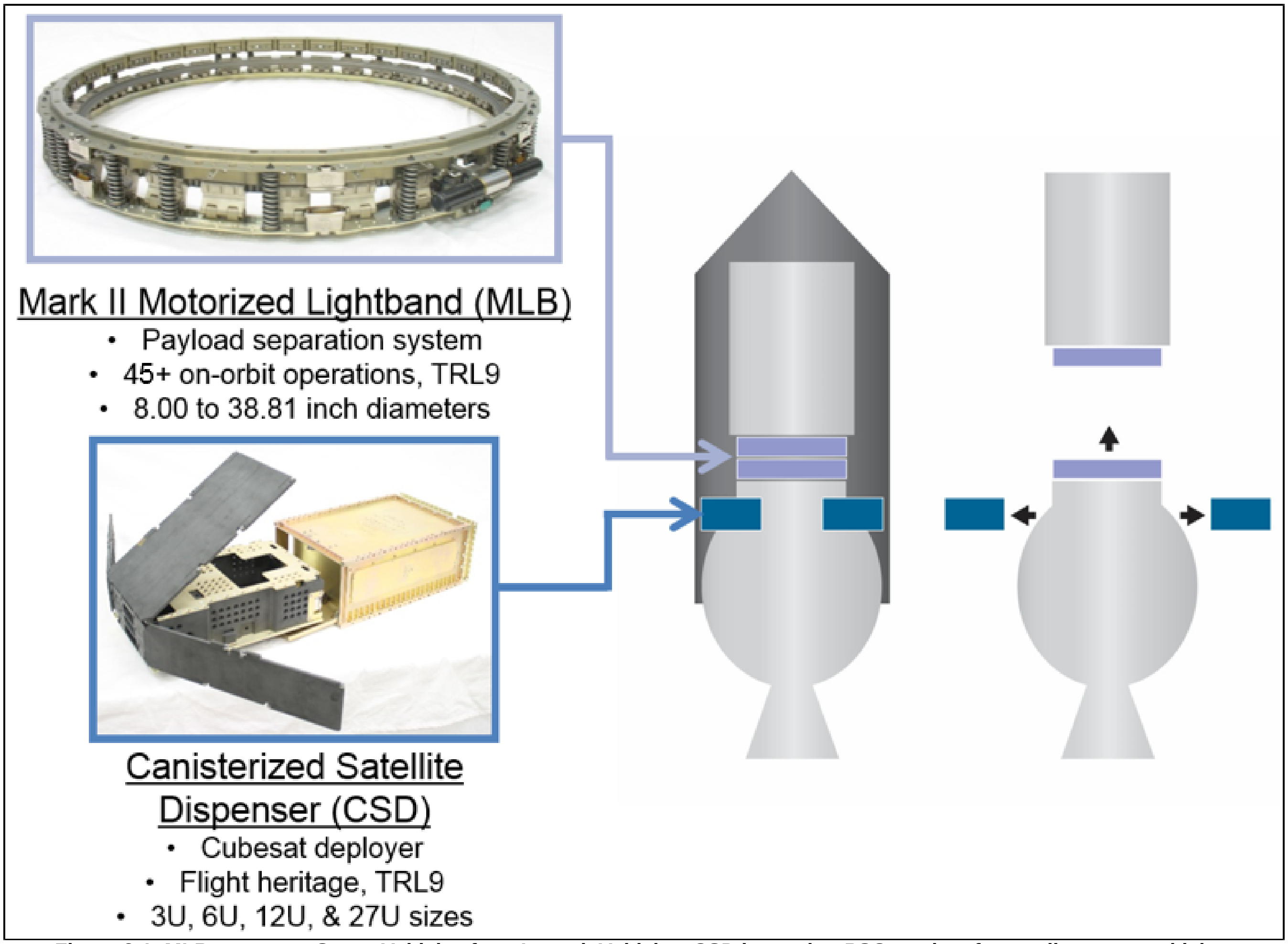


Figure 2-1: MLB separates Space Vehicles from Launch Vehicles. CSD is another PSC product for smaller space vehicles.

Figure 2-2: Two of NASA's lunar GRAIL satellites separate from a Delta II in 2011 using 2X MLB19.848

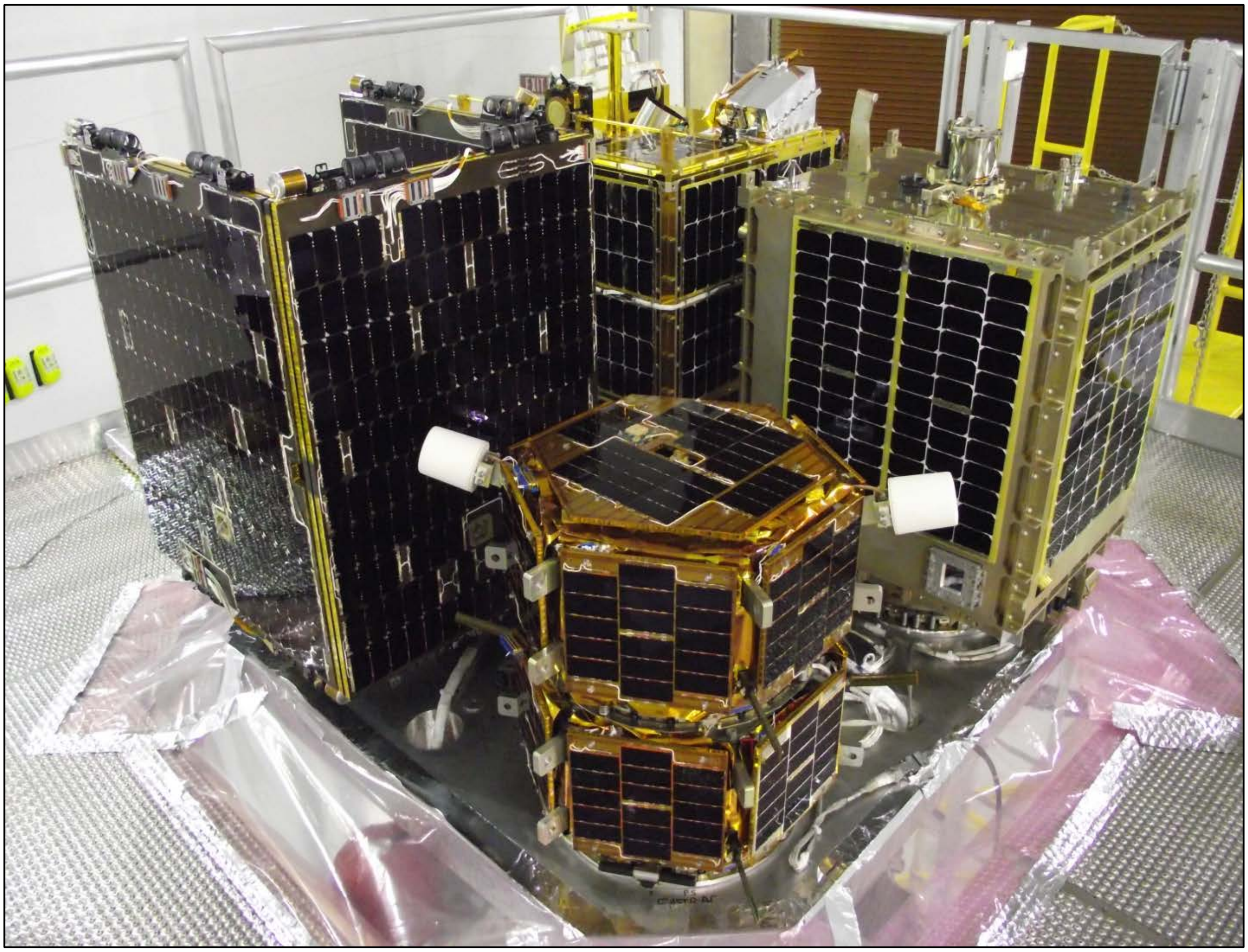


Figure 2-3: Four MkII and one MkI Lightbands used to separate five spacecraft on STP S-26 in November 2010

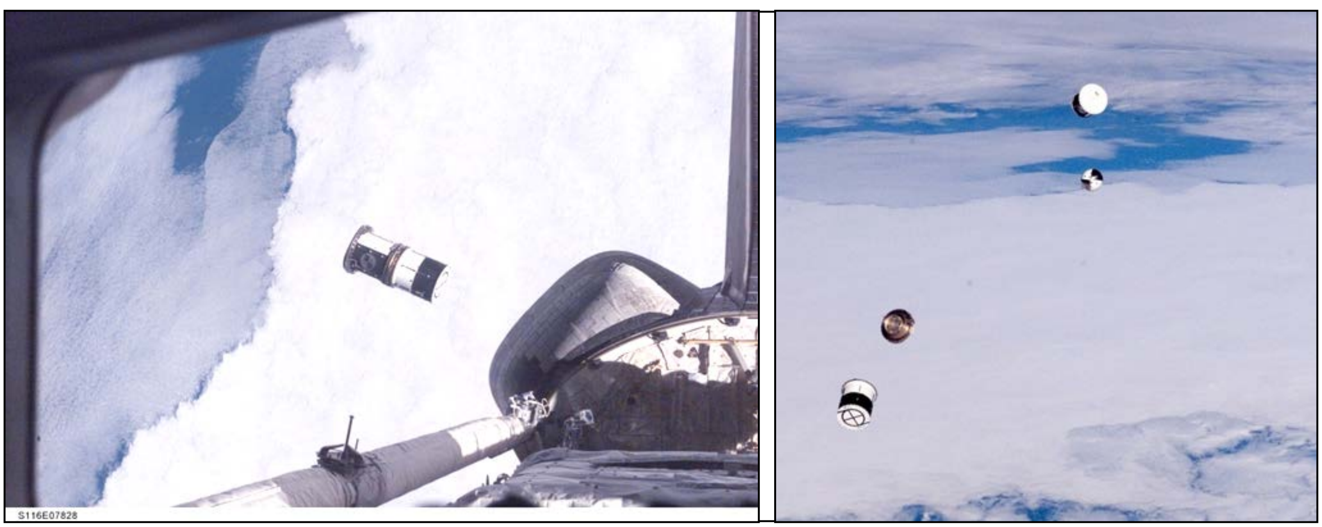


Figure 2-4: ANDE-1 Separation from Shuttle (STS-116). Three MkI Lightbands were used.

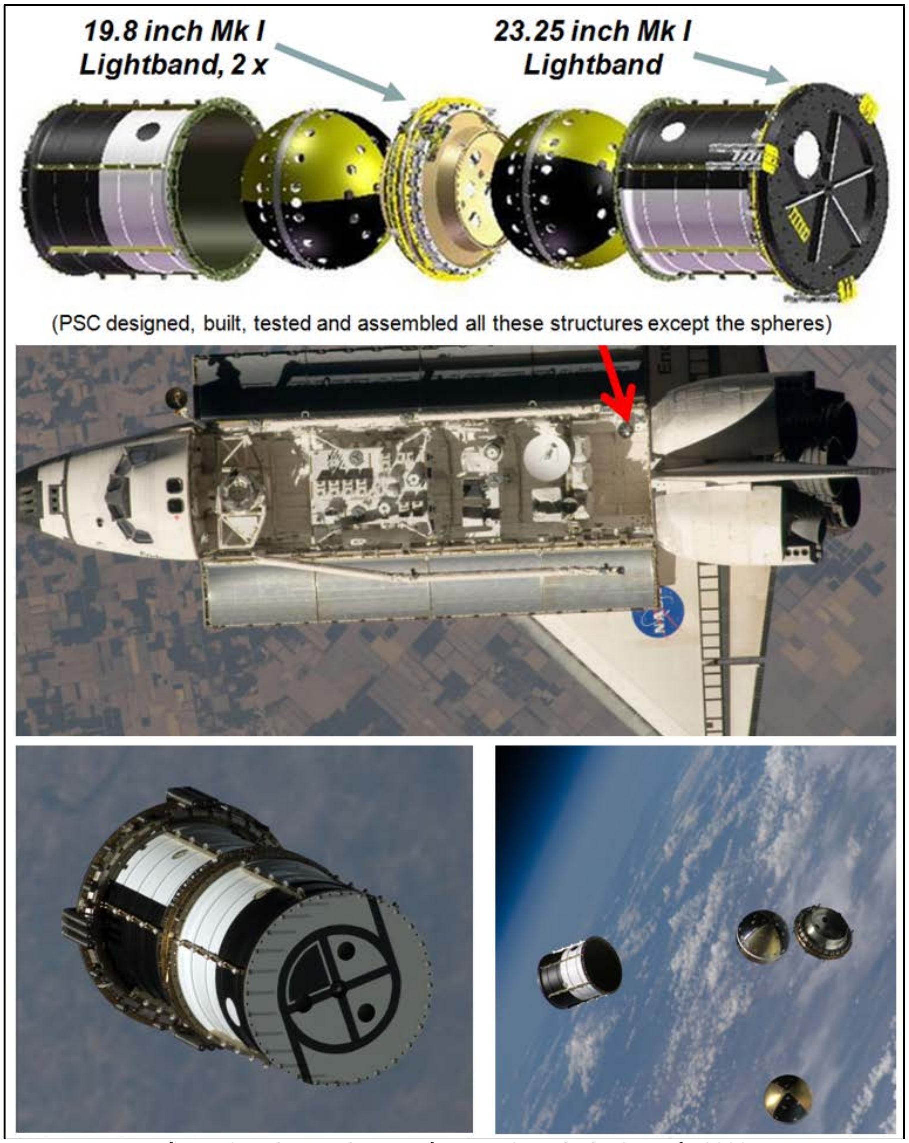


Figure 2-5: CAPE-ICU II and ANDE-2 on STS 127, July 2009

Figure 2-6: Three MkII Lightbands (38.8, 31.6 and 15.0 inch diameter) are used on the IBEX Program.

Figure 2-7: Lightbands on ESPA (STP-1) on an Atlas V

Figure 2-8: Two Lightbands installed on a lunar payload prior to launch[1]

[1] Source: http://www.nasa.gov/sites/default/files/ladee_encapsulation.jpg

3. Why Choose Lightband?

The Lightband has many advantages over competing products:

1. **Technology Readiness Level 9 rating**. TRL 9 is the maximum attainable level of this measure which is used by US Government agencies to assess the maturity of evolving technologies.
2. **Test-verified**. Each Lightband goes through environmental testing before delivery to prove separation capability on orbit.
3. **Minimal reset time.** Lightband can be operated by customers and reset in minutes. Competing products require hours to reset.
4. **Lightweight**. The Lightband is about one third of the weight of a typical clamp band.
5. **Low-height**. About one half of the height of a typical clamp band.
6. **Non-pyrotechnic**. The Lightband generates no debris upon or after separation.
7. **Low-shock.** The Lightband generates very low shock relative to other separation systems.
8. **All-inclusive product.** The Lightband is delivered with Separation Springs, Switches and Connectors included within its assembly and does not require additional brackets.
9. **No consumables.** Motor-driven, eliminating the need for refurbishment or consumable initiators.
10. **Pyro-pulse compatible.** The Lightband can be separated via a pyro-pulse signal.
11. **Flight heritage.** Flight-proven over 45 times.
12. **Simplified procurement**. The Lightband is priced on GSA schedule to streamline procurement.
13. **Ideal for ISS.** The Lightband can be configured so as not to require auxiliary mechanical inhibits. This is useful for unique mission redundancy requirements such as those of International Space Station payloads.

4. Lightband Flight History

No Lightband has ever failed to separate on orbit. To date, the Lightband has operated successfully in flight more than 45 times. See the flight heritage section of PSC's website for the most up-to-date list (http://www.planetarysystemscorp.com).

The Lightband has been used on the following launch vehicles:

- Antares
- Athena
- Atlas V
- Delta II
- Delta IV
- Delta IV Heavy
- Falcon 1
- Falcon 9
- Minotaur I
- Minotaur IV
- Minotaur V
- Pegasus XL
- Space Shuttle
- Vega

Figure 4-1: A Lightband installed on the TacSat-2 mission

5. Lightband Capabilities and Dimensions

	Parameter		See Doc. Section	Value									
Size	Bolt Circle Diameter ± 0.01 [in]		-	8.000	11.732	13.000	15.000	18.250	19.848	23.250	24.000	31.600	38.810
	Number of Fasteners			12	18	20	24	28	28	32	36	48	60
Dimensions	Stay-Out Dimensions ± 0.02 [in] (1) (2)	A [in]	6.1	10.04	13.76	15.02	17.02	20.27	21.87	25.42	26.17	33.76	40.97
		B [in]		7.00	10.83	12.11	14.14	17.41	19.00	22.41	23.18	30.80	38.03
		C [in]		5.93	9.60	10.58	12.41	15.48	17.07	20.28	20.95	28.17	35.30
		D [in]		0.56	2.67	3.36	4.43	6.12	6.93	8.67	9.06	12.92	16.55
		E [in]		5.39	7.50	8.19	9.25	10.94	11.76	13.50	13.89	17.74	21.38
		F [in]		1.03	1.03	1.03	1.03	1.03	1.03	1.05	1.05	1.15	1.15
Mass Properties	Mass ± 5% [lb_m] (3)	Upper Assembly	-	0.78	1.15	1.27	1.47	1.83	1.99	2.36	2.42	3.61	4.51
		Lower Assembly		2.50	3.47	3.76	4.32	5.05	5.25	6.08	6.53	8.77	10.57
		Total		3.28	4.62	5.03	5.79	6.88	7.24	8.44	8.95	12.38	15.08
	Center of Mass ± 0.1 [in] (3)	X_{LB}	-	1.09	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
		Y_{LB}		1.11	1.08	1.06	1.04	1.12	1.14	1.14	1.10	0.98	0.95
		Z_{LB}		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		X_{LB}, Upper Assembly	-	1.68	1.68	1.68	1.68	1.68	1.68	1.67	1.66	1.60	1.60
		Y_{LB}, Upper Assembly		-0.08	-0.09	-0.09	-0.09	-0.10	-0.10	-0.10	-0.10	-0.12	-0.12
		Z_{LB}, Upper Assembly		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		X_{LB}, Lower Assembly	-	0.88	0.85	0.85	0.86	0.85	0.84	0.84	0.84	0.86	0.85
		Y_{LB}, Lower Assembly		1.19	1.44	1.41	1.37	1.51	1.58	1.60	1.52	1.44	1.39
		Z_{LB}, Lower Assembly		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Inertia ± 10% [lb_m*in^2] (3)	I_{XX} (4)	-	51.6	155.8	207.4	316.5	559.1	696.9	1,120.9	1,266.7	3,051.9	5,622.2
		I_{YY} (4)		21.8	67.4	91.0	140.4	249.8	311.9	508.1	577.6	1,423.9	2,648.4
		I_{ZZ} (4)		32.2	92.2	120.0	180.4	313.9	390.6	619.4	696.1	1,637.1	2,985.1
		I_{XX}, Upper Assembly	-	12.9	40.8	55.4	85.3	156.0	199.7	325.0	355.3	916.2	1,720.6
		I_{YY}, Upper Assembly		6.6	20.9	28.3	43.5	79.2	101.0	164.2	179.4	462.2	866.3
		I_{ZZ}, Upper Assembly		6.4	20.1	27.3	42.1	76.8	99.0	161.3	176.3	454.8	855.5
		I_{XX}, Lower Assembly	-	34.5	108.3	146.2	228.9	398.6	490.6	789.0	904.6	2,129.5	3,891.1
		I_{YY}, Lower Assembly		14.2	44.6	61.0	96.8	169.0	209.7	342.9	397.0	960.3	1,781.6
		I_{ZZ}, Lower Assembly		21.8	65.9	88.0	134.7	231.0	284.2	450.1	511.8	1,174.7	2,116.2
Loading & Boundaries	Maxium Loads (5)	X_{LB} axis [lb]	6.10	11,280	16,920	18,800	22,560	26,320	26,320	30,080	33,840	45,120	56,400
		Y_{LB} or Z_{LB} axis [lb]		2,322	3,483	3,870	4,644	5,418	5,418	6,192	6,966	9,288	11,610
		Moment about Y or Z_B [in*lb_f]		22,560	49,626	61,100	84,600	120,085	130,600	174,840	203,040	356,448	547,221
	Stiffness about X_{LB} ±25% [lb_f/in] (6)		6.6	1.80E+06	2.64E+06	2.93E+06	3.38E+06	4.11E+06	4.47E+06	5.23E+06	5.40E+06	7.11E+06	8.73E+06
	Stiffness about Y_{LB} or Z_{LB} ±25% [in*lb_f/rad] (6)		6.6	1.40E+07	4.43E+07	6.02E+07	9.25E+07	1.67E+08	2.14E+08	3.44E+08	3.79E+08	8.65E+08	1.60E+09
	Required flatness of adjoining structure if X.XXX structure is "flexible" [in] (7)		6.11	0.0028	0.0042	0.0046	0.0053	0.0065	0.0071	0.0083	0.0085	0.0112	0.0138
	Required flatness of adjoining structure if X.XXX structure is "stiff" [in] (7)		6.11	0.0021	0.0031	0.0035	0.0040	0.0049	0.0053	0.0062	0.0064	0.0084	0.0103
Electrical	Nominal Separation Signal		7.6	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s	24-32V for 0.5s
	Mean Time to Separate [s] (24-32V, nominal temperature)		7.6	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065
	Std. Dev Time to Separate [s] (nominal voltage & temperature)		7.6	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Resistance from Upper Ring to Lower Ring [Ω]		7.10	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002	0.007 ± 0.002
Thermal	Thermal Resistance [°C/W]		8.4	0.392	0.267	0.241	0.209	0.172	0.158	0.135	0.130	0.099	0.081
	Survival Limits [°C]		8.2	-68 to +145	-68 to +146	-68 to +147	-68 to +148	-68 to +149	-68 to +150	-68 to +151	-68 to +152	-68 to +153	-68 to +154
	Operating Limits [°C]		8.2	-54 to +128	-54 to +128	-54 to +128	-54 to +128	-54 to +128	-54 to +128	-54 to +128	-54 to +128	-54 to +128	-54 to +128
	Solar Absorptivity (α) [-]		8.3	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35	0.27 to 0.35
	Emissivity (ε) [-]		8.3	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84	0.76 to 0.84
Shock	Generated Shock at Upper Ring, 100 Hz [g]		9.1	19	25	27	31	34	35	38	39	46	51
	Generated Shock at Upper Ring, 1,000 Hz [g]		9.1	381	505	546	617	680	709	768	780	937	1,038
	Generated Shock at Upper Ring, 10,000 Hz [g]		9.1	381	505	546	617	680	709	768	780	937	1,038
Sep. Rates	Maximum Rotation Rate [deg/s]		6.21	0.0±5.0	0.0±5.0	0.0±5.0	0.0±5.0	0.0±5.0	0.0±5.0	0.0±5.0	0.0±5.0	0.0±5.0	0.0±5.0
	Nominal Rotation Rate [deg/s]		6.21	0.0±1.0	0.0±1.0	0.0±1.0	0.0±1.0	0.0±1.0	0.0±1.0	0.0±1.0	0.0±1.0	0.0±1.0	0.0±1.0
	Separation Velocity [ft/s] (varies with payload mass)		6.21	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0	0.25 to 2.0
Accessories	Max Qty. of Separation Springs [-]		-	14	18	24	24	24	24	24	24	24	24
	Max Qty. of Lightband Comp. Tools [-] (8)		-	6	12	14	16	18	20	22	26	34	46
	Max Qty. of Sum of Sep. Connectors, Switches and Roll Brackets (9)		-	4	4	4	6	6	6	8	8	12	12
Lifecycle	Usable Life Before Potential Refurb. [cycles]		6.15	60	60	60	60	60	60	60	60	60	60
	Time required to re-stow [min]		-	1	1	1	1	1	1	1	1	1	1
	Refurbishment Required After a Separation?		-	No	No	No	No	No	No	No	No	No	No
	Special tools required?		-	No	No	No	No	No	No	No	No	No	No
	Max. Storage Duration (Stowed) [yrs]		13	1	1	1	1	1	1	1	1	1	1
	Max. Storage Duration (SFF) [yrs]		13	1	1	1	1	1	1	1	1	1	1
	Max. Storage Duration (Deployed) [yrs]		13	3	3	3	3	3	3	3	3	3	3

(1) The customer-supplied wiring harness may exceed these dimensions.
(2) The use of Roll Bracket Assemblies or high quantity of LCTs may exceed Stayout Diameter A.
(3) Does not include Separation Springs or Accessories.
(4) Measured about CM in stowed state.
(5) Applied independently. Values are qualification loads scaled by a factor of 0.5.
(6) Does not include compliance of the joint to the adjoining structure. Can be test-correlated to increase precision.
(7) If in doubt, contact PSC. See discussion of features on adjoining structures in Section 6.8.
(8) Installing a high quantity of Springs may prohibit the installation of the maximum quantity of LCTs.
(9) For example, on an MLB15 there may be 4 separation switches and 2 separation connectors (4 + 2 = 6).

Table 5-1: Lightband capabilities and dimensions

6. Mechanical Properties

6.1 Dimensions

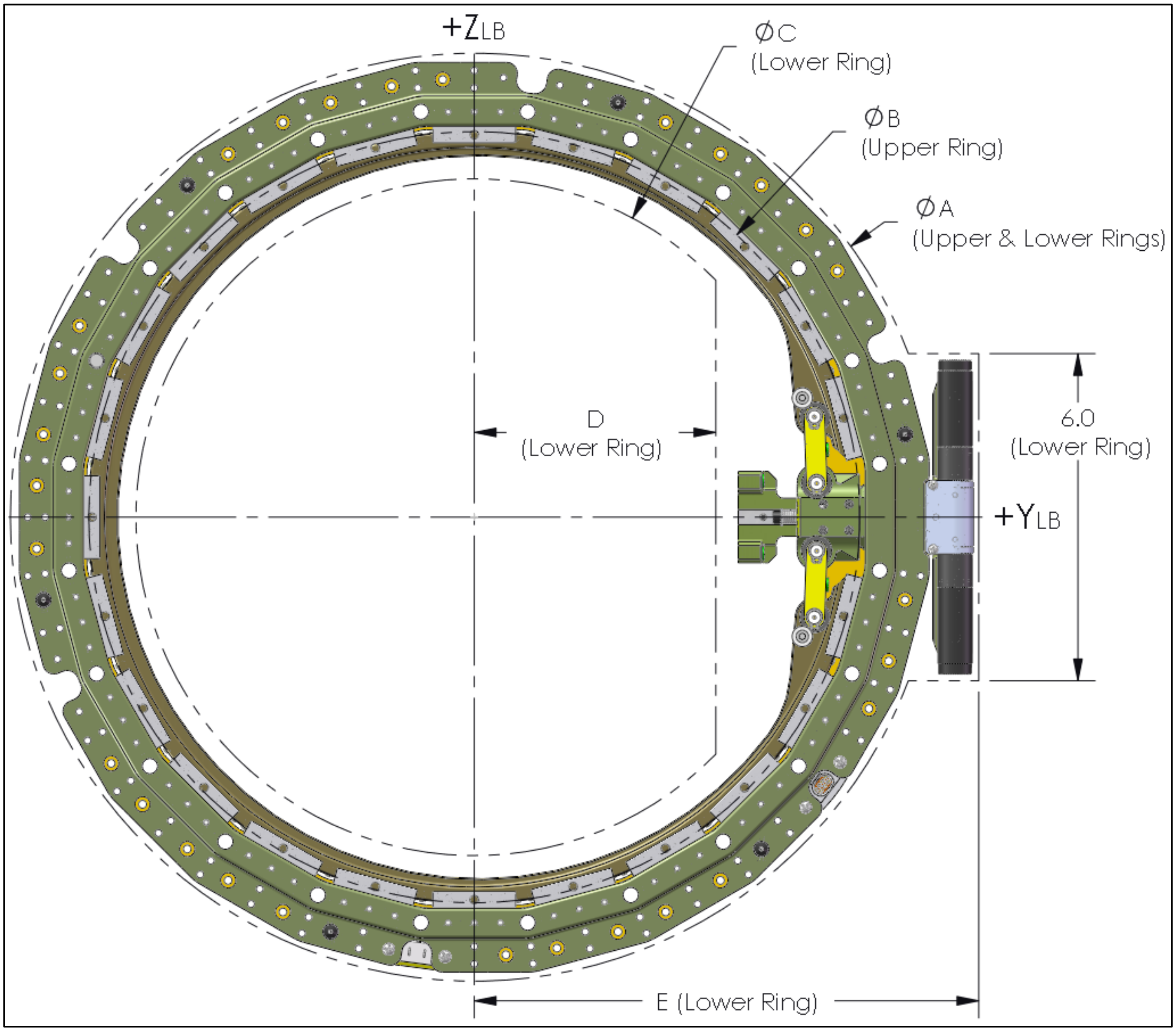


Figure 6-1: Top view of Lightband, see Table 5-1 for variable dimension values

The dimensions shown in Figure 6-1 and Figure 6-3 as variables vary with diameter and are defined in Table 5-1. Dimensions 'C' and 'D' include the separation event when the Retaining Ring and Sliding Tube snap inward. The dimensions shown as constants do not vary by diameter. The customer-supplied wiring harness is not shown. Harness design, discussed in Section 7.3, can substantially increase the volume associated with the separation system.

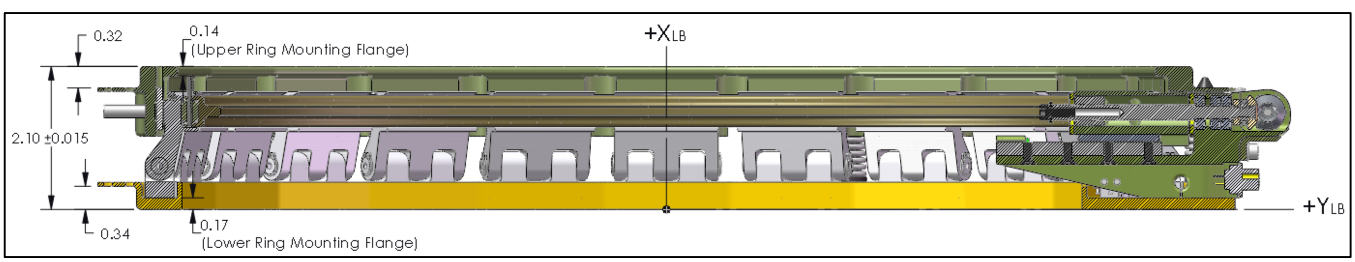


Figure 6-2: A sectional view of a 15 inch Lightband.

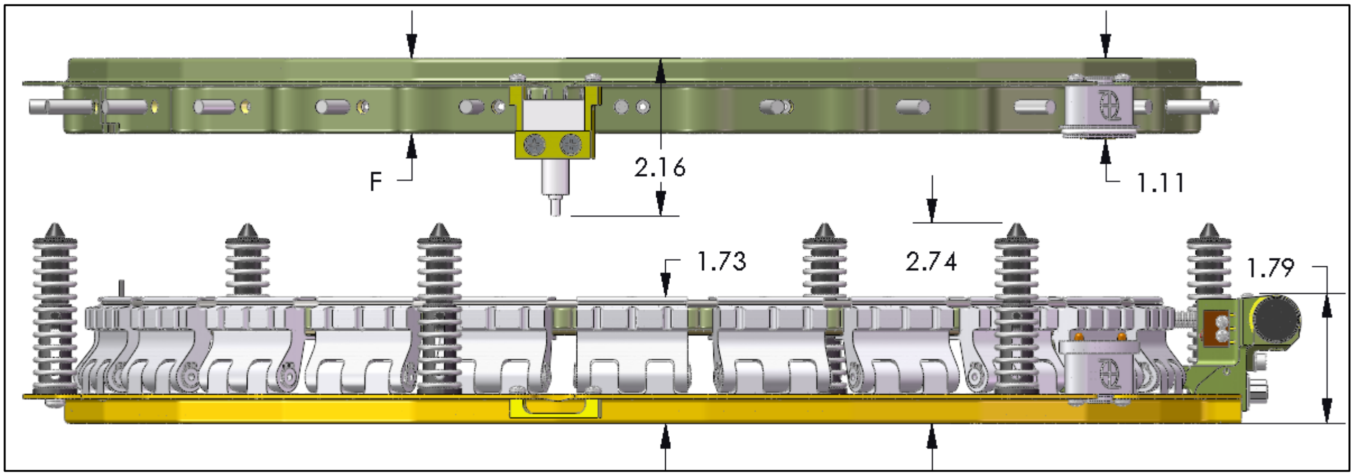


Figure 6-3: The deployed (or separated) view. The Springs and Switches are shown fully elongated

6.2 Tolerance on Dimensions

PSC Document *3000233 PSC Tolerance Standards* defines all PSC standards regarding measurement tolerance. For reference, distance tolerances are shown in Table 6-1.

Precision	Tolerance [unit]
x.xxxx	± 0.001
x.xxx	± 0.005
x.xx	± 0.010
x.x	± 0.030
x	± 1.000

Table 6-1: PSC distance tolerances[2]

[2] Source: PSC Document 3000233.

6.3 Lightband Description

The coordinate system for the Lightband is shown below. The $+X_{LB}$ axis originates from the Lower Ring bottom plane and points towards the Upper Ring. The $+Y_{LB}$ axis passes through the center plane of the Motor Assembly. The Lightband Upper and Lower Rings are engraved with $+Y_{LB}$ and $+Z_{LB}$ during manufacture. Unless otherwise noted, all axes in this document refer to the Lightband coordinate system and all dimensions are given in inches.

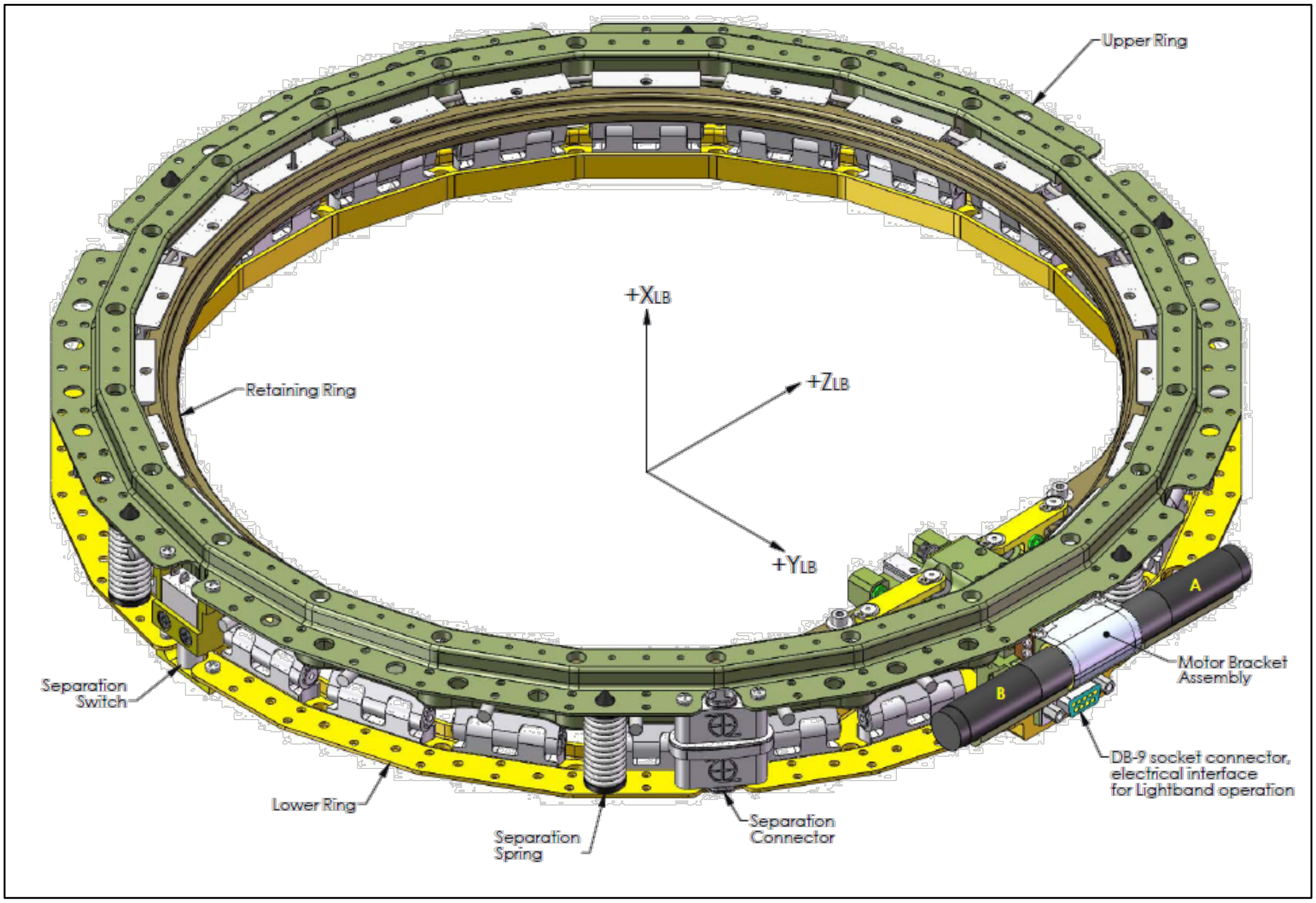


Figure 6-4: 15 inch diameter Lightband shown stowed

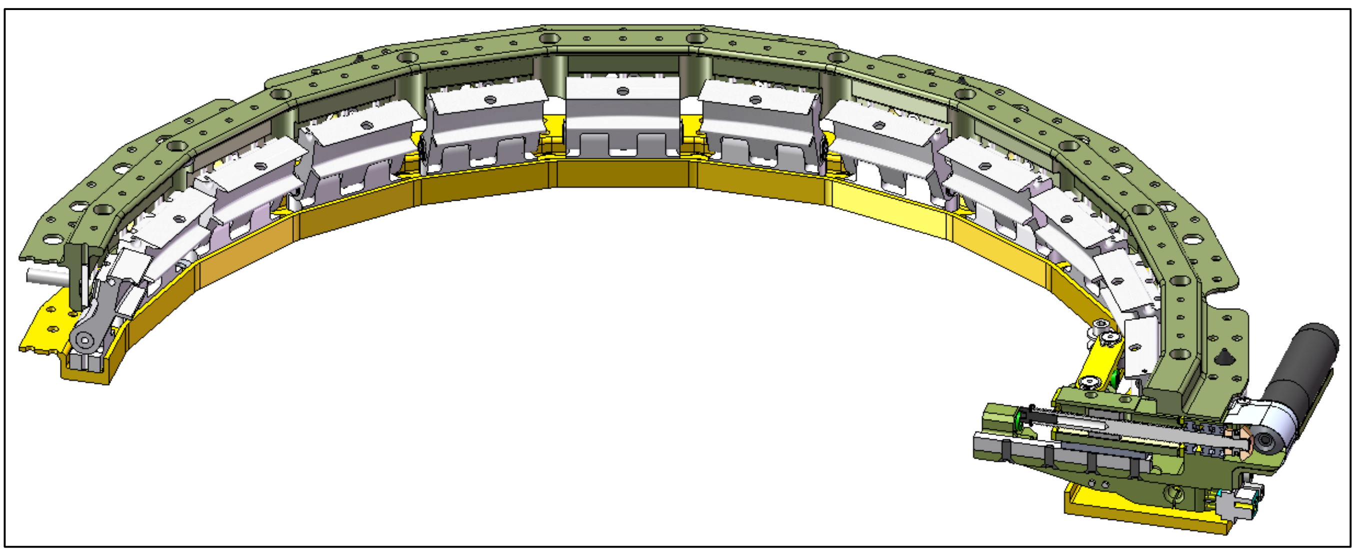


Figure 6-5: The Leaves beginning to disengage during deployment, Retaining Ring and Leaf Retaining Cord removed (section view)

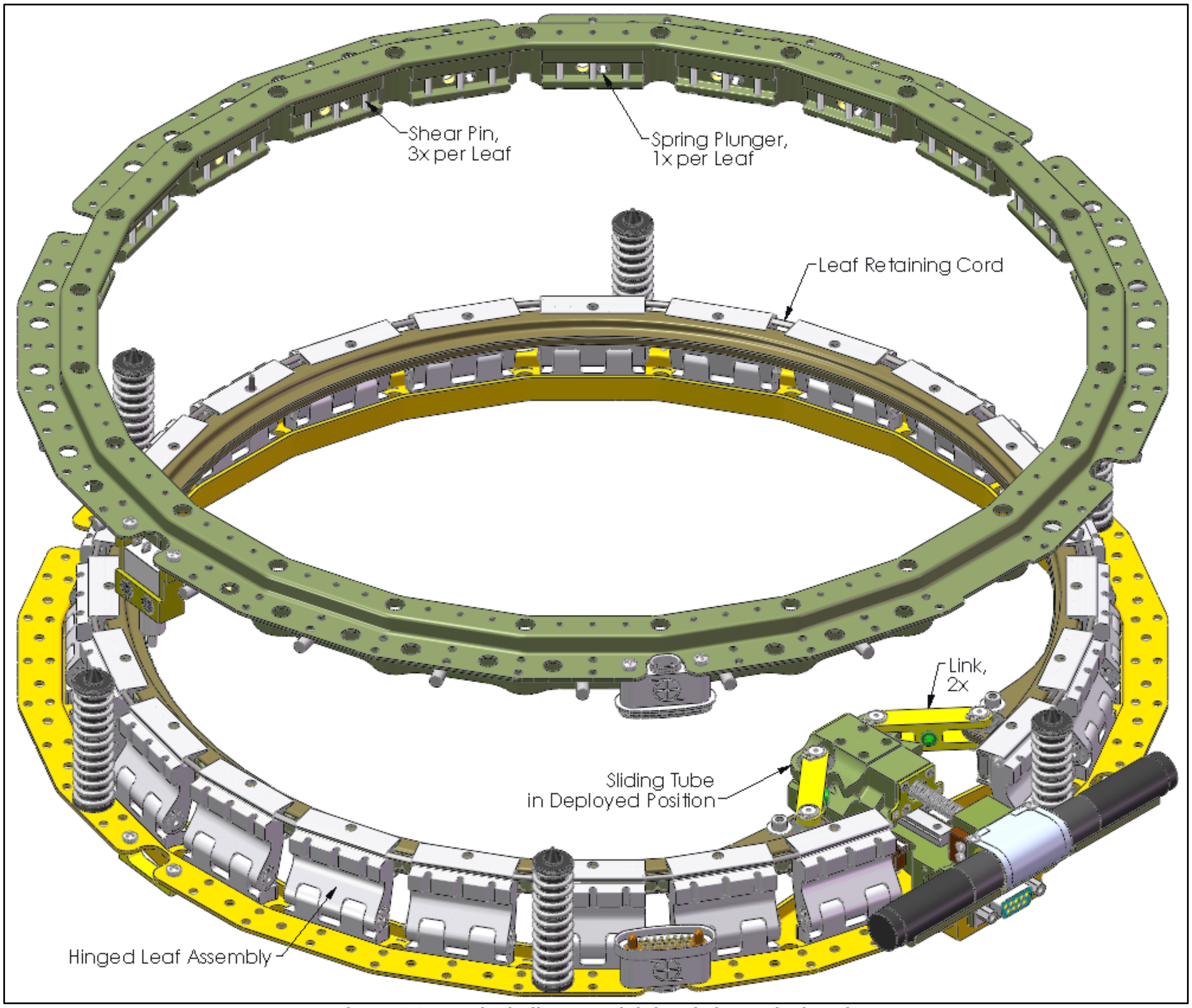


Figure 6-6: A 15 inch diameter Lightband shown deployed

6.4 How the Lightband Works

Videos showing the Lightband operating on the ground and on-orbit are available at www.planetarysystemscorp.com.

Figure 6-7 shows the Lightband in the stowed state. The Retaining Ring is in compression (black arrows) pressing the Leaves outward into the Upper Ring. The Links are over-centered and the motors are not powered.

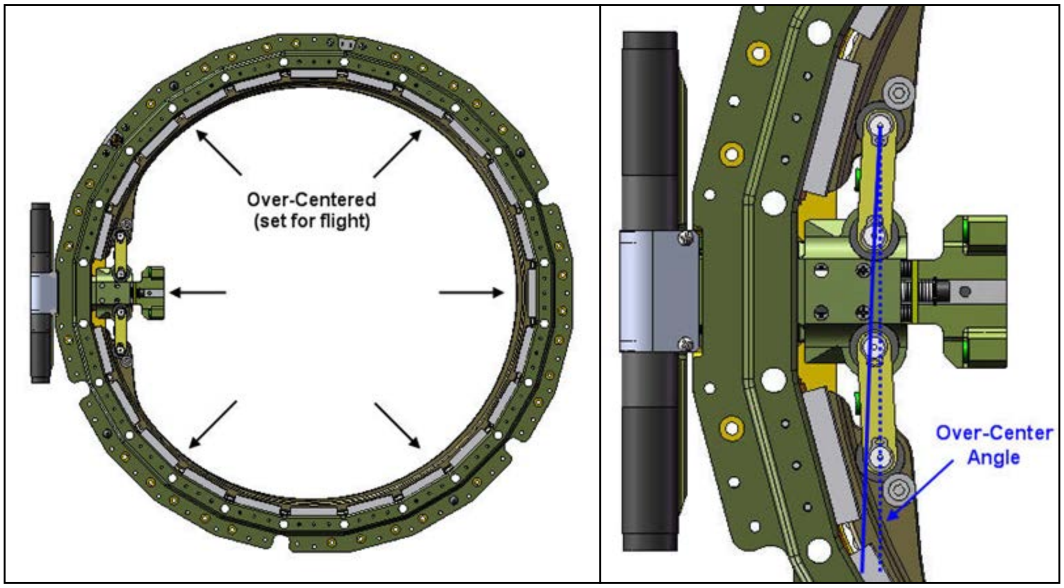


Figure 6-7: The Lightband in the stowed state (top-view)

Figure 6-8 shows the Lightband in the initiated state. Upon deployment initiation, the motors are powered causing the mechanism to snap inward in approximately 0.065 seconds allowing the Retaining Ring to contract.

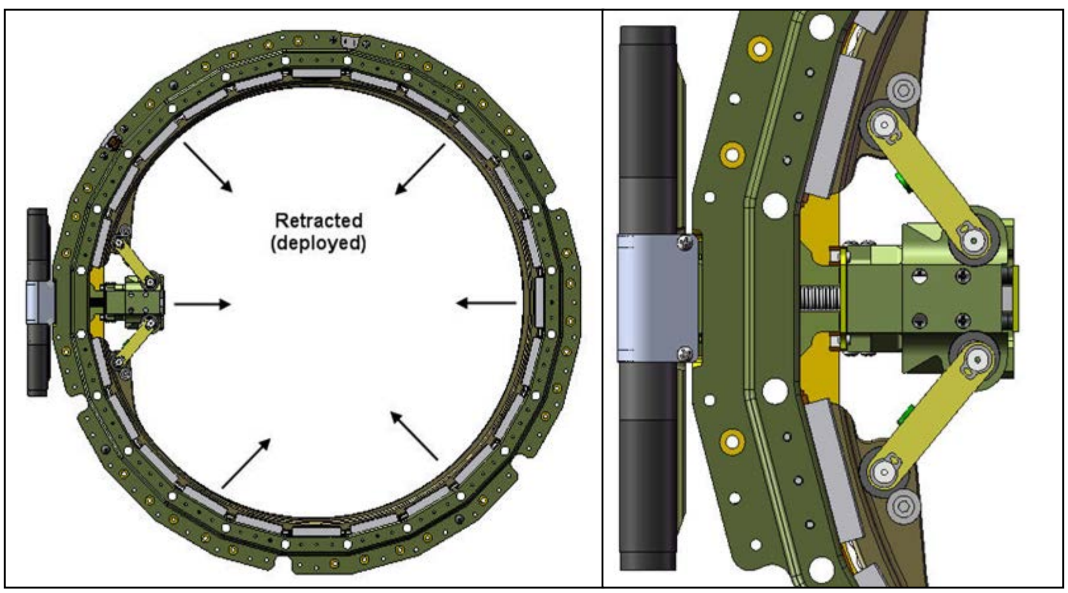


Figure 6-8: The Lightband in the initiated state

The Leaf Retaining Cord provides a constant radial force inward that causes all the Leaves to bear upon the Retaining Ring. After the motors have been initiated, the Retaining Ring no longer reacts the inward Leaf Retaining Cord force. The Spring Plungers, fastened to the Upper Ring, then cause the Leaves to disengage from the Upper Ring after the Sliding Tube has snapped inward. See Figure 6-9 and Figure 6-10.

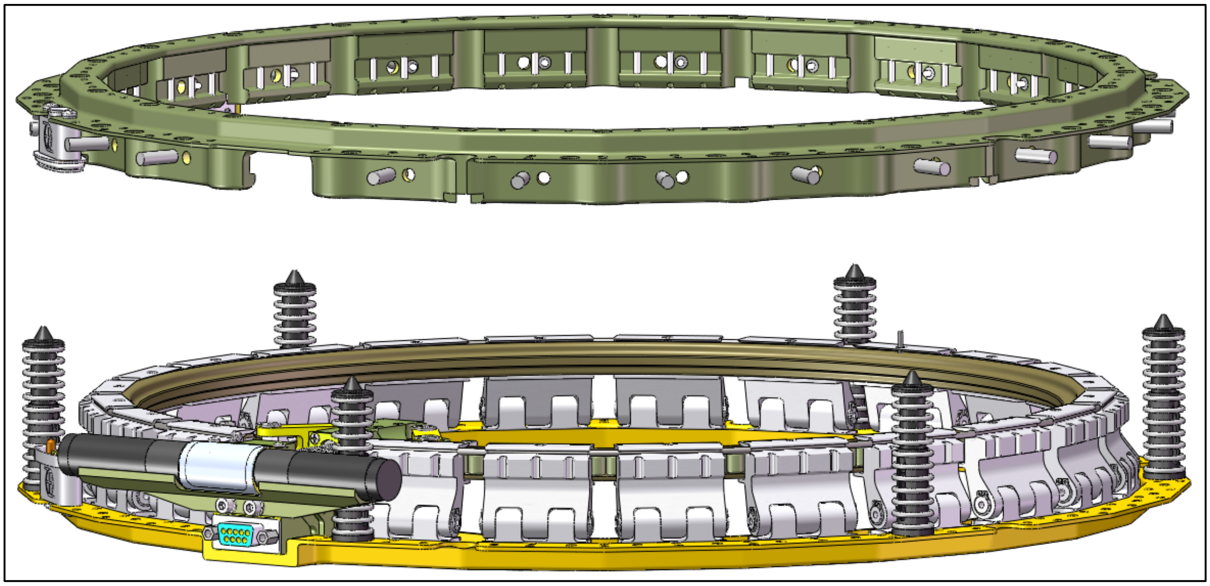


Figure 6-9: The Lightband in the deployed (or separated) state

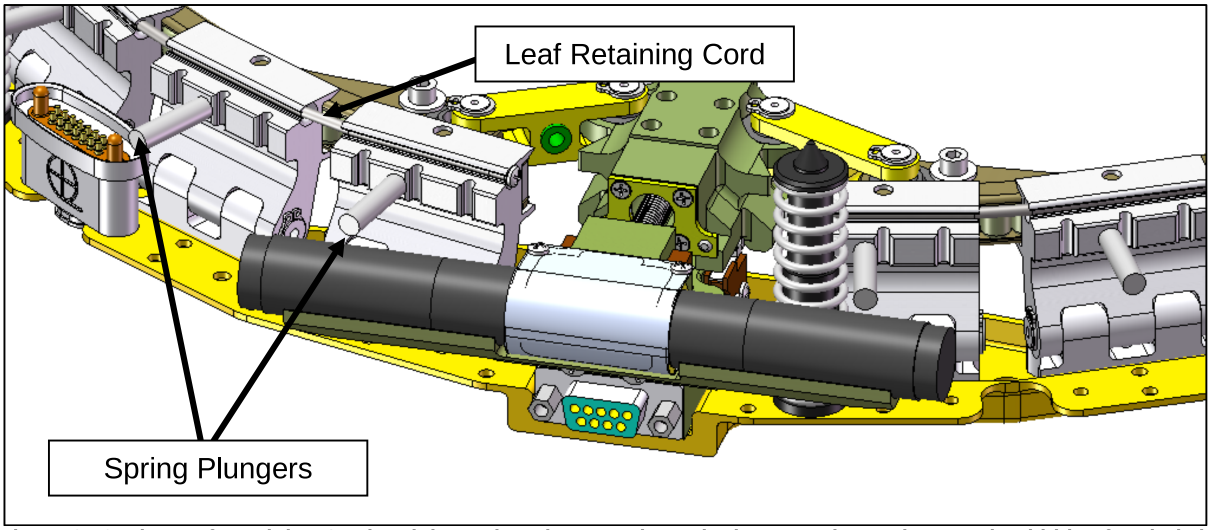


Figure 6-10: The Leaf Retaining Cord and the spring plungers shown in the stowed state (Upper Ring hidden for clarity)

Figure 6-11 illustrates the Leaves disengaging due to the force from the Spring Plungers, allowing the Separation Springs to push the rings apart.

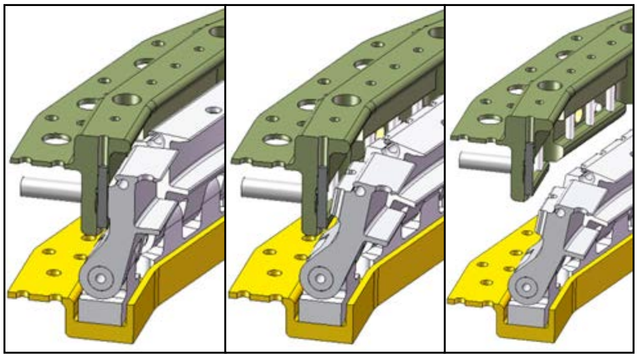


Figure 6-11: The Lightband shown deploying (or separating)

6.5 How the Motor Bracket Assembly Works

The Motor Bracket Assembly (MBA) is the actuator of the Lightband. In the MBA, two DC brush Motors connect to Bevel Gears. Stainless steel Bevel Gears connect to a brass common Bevel Gear and that common Bevel Gear connects to the stainless steel Ball Screw. The Ball Screw connects to a Ball Nut which bears upon the Stow or Deploy End Plate, depending on the Lightband operation. The Sliding Tube encloses the Ball Nut and is fastened to the Linear Way which slides on the Rail. The Sliding Tube is connected to the Links via spherical bearings which in turn control the motion the Retaining Ring.

The Motor Bracket constrains the linear motion of the Sliding Tube with elastomeric (non-out-gassing) bumpers at the deploy end and with hard stops at the stow end. The lubricants, Braycote 601-EF and molybdenum disulfide, are space-qualified and non-outgassing. The Limit Switches are arranged to cut power when operational physical limits (stow, set-for-flight, and deploy) are reached.

All of the set screw junctions in the MBA are redundant and bear upon flats or bores. All fasteners are staked with Arathane after being torqued. The Motors are redundantly fastened to the Motor Bracket and staked to the Motor Supports. The motor pinions between the Motor and Planetary Gear are connected to the motor shafts redundantly (a weld and a shear pin). Except for the spherical bearings, there is no sliding friction; all of the motion of this assembly is strictly rolling.

The deploy operation is fully reversible, though it takes more energy to stow than deploy the Lightband. As a reliability feature, the Lightband will not stow if only one Motor is operable. If the Lightband cannot be stowed, it cannot fly. However, the Lightband will deploy and set-for-flight with one Motor.

A flex circuit connects the Limit Switches and Motors to the DB-9 socket connector fastened to the Motor Bracket. Section 7 of this document describes electro-mechanical operation of the Lightband.

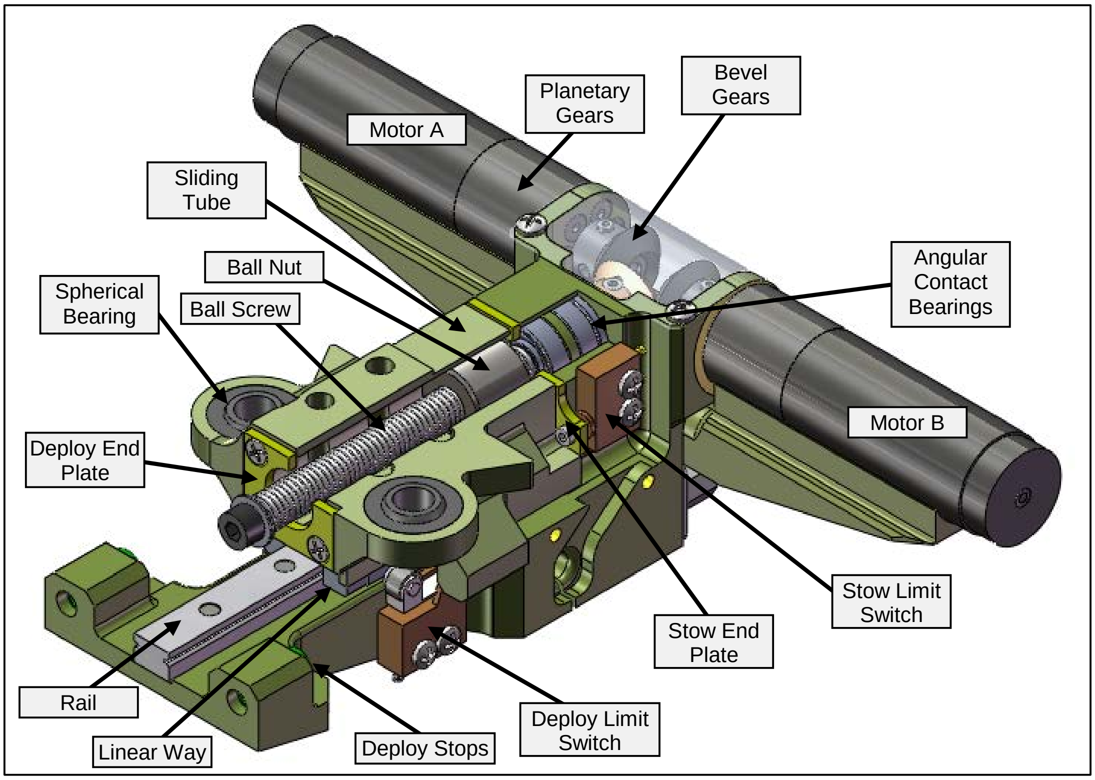


Figure 6-12: Motor Bracket Assembly shown in the stowed state (with Sliding Tube shown as section for clarity)

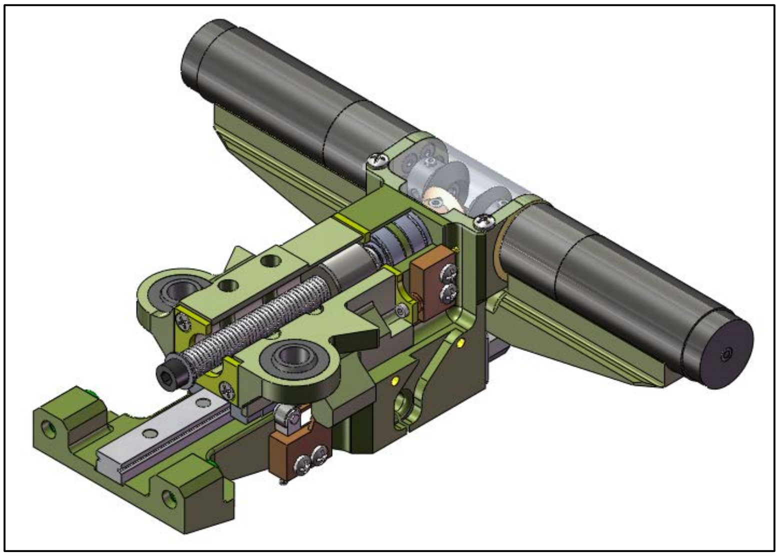


Figure 6-13: Motor Bracket Assembly in the stowed state

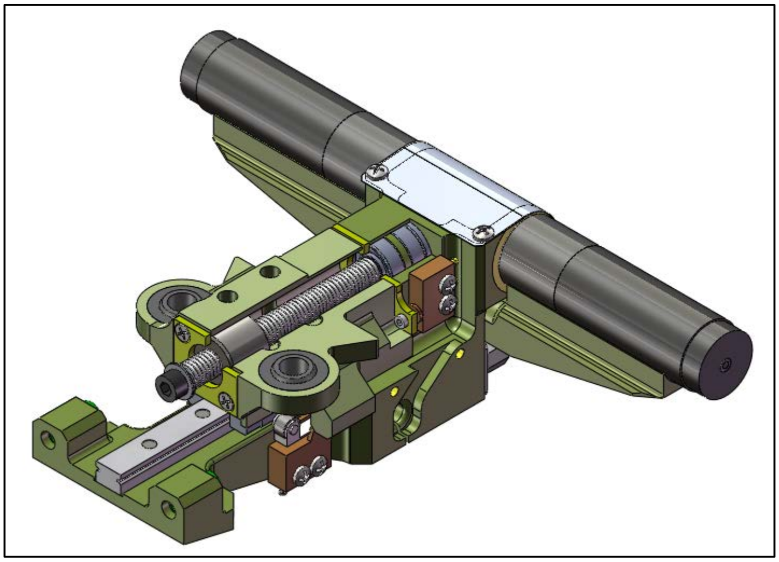


Figure 6-14: Motor Bracket Assembly in the set-for-flight state

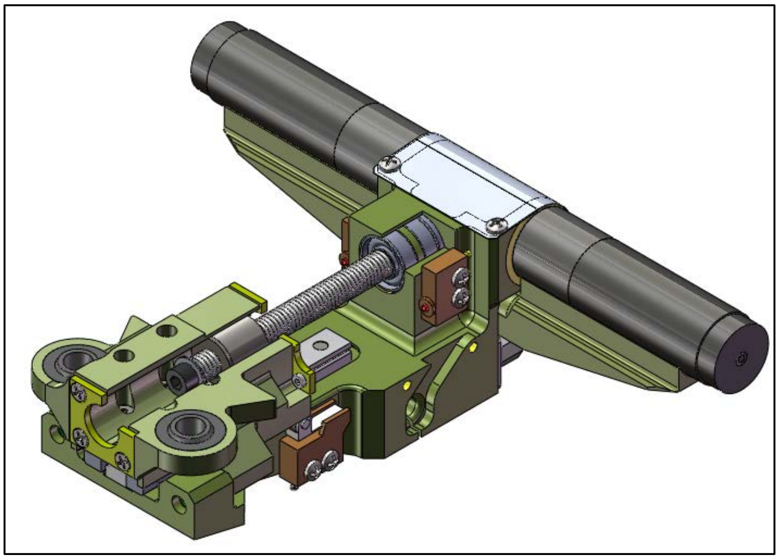


Figure 6-15: Motor Bracket Assembly in the deployed state

6.6 Stiffness

Stiffness is major design driver when determining which Lightband size is required for a payload. Payload stack stiffness increases with the cube of the Lightband diameter. For example, a 15 inch diameter Lightband is about 6.6 times stiffer than an 8 inch diameter Lightband, but weighs only twice as much. Additionally, the first lateral mode frequency of the payload stack increases with the 3/2 power of Lightband diameter. Often, customers select the smallest allowable Lightband and thus payload stiffness is barely above allowable minimums. This can increase risk of mission failure due to unintended stack dynamics. Prudent customers often use a larger Lightband diameter than required to gain stiffness margin with only a small increase in weight. The method used to determine stiffness of the Lightband is shown in the latest revision of PSC Document *2000541 Lightband Stiffness*. Stiffness values are shown in Table 5-1. Higher fidelity stiffness estimations of the Lightband can be determined via FEM.

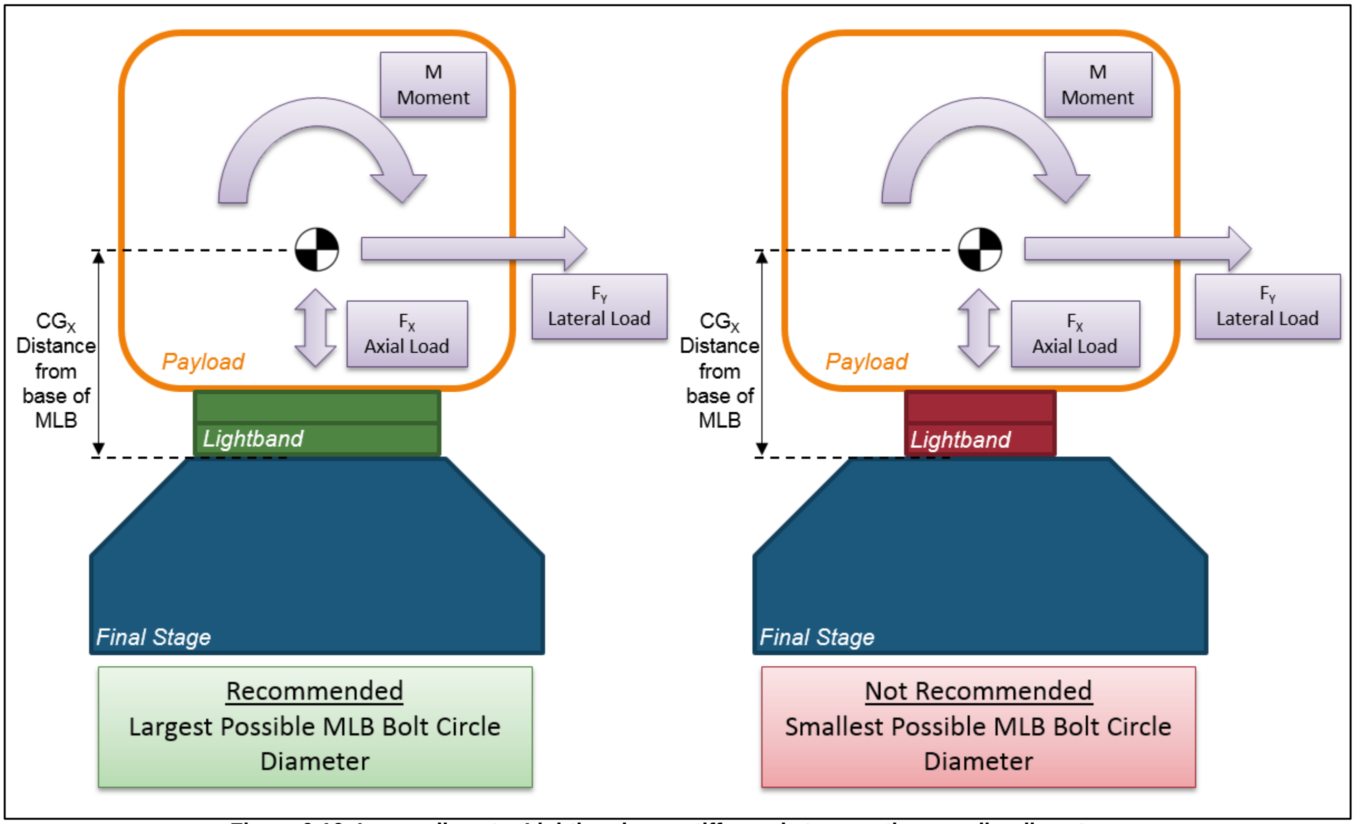


Figure 6-16: Larger diameter Lightbands are stiffer and stronger than smaller diameters

6.7 Joint Compliance

The compliance of the bolted joint from the Lightband to adjoining structures can have a substantial effect on the overall stiffness. The stiffness reported in Table 5-1 does not include joint compliance. Table 6-2 shows the normalized results of a study of stiffness for a specific Lightband program and illustrates that joint compliance reduces stiffness in all directions. The data comes from the test of a 38.810 inch diameter Lightband and is for example rather than design purposes.

It can be assumed that the effect of joint compliance on any size Lightband is the same as shown in Table 6-2.

Item	Normalized X_{LB} Axis Stiffness [-]	Normalized Y_{LB} & Z_{LB} Axis Stiffness[-]	Normalized R_X Rotational Stiffness [-]	Normalized R_Y or R_Z Rotational Stiffness [-]
Lightband without joint compliance	1.00	1.00	1.00	1.00
Lightband with joint compliance	0.74	0.99	1.00	0.75

Table 6-2: The effect of joint compliance on stiffness[3]

6.8 Discussion of Features on Adjoining Structures

In order to maximize the stiffness of the satellite stack including the Lightband, engineers should design robust features in the structures adjoining the Lightband. As the analysis in Table 6-3 shows, thick flanges, small moment arms, and chamfers (or large radii) create much stiffer and lighter structures.

[3] Source: Moog CSA Engineering Document 20008507B and PSC Document 2000541A.

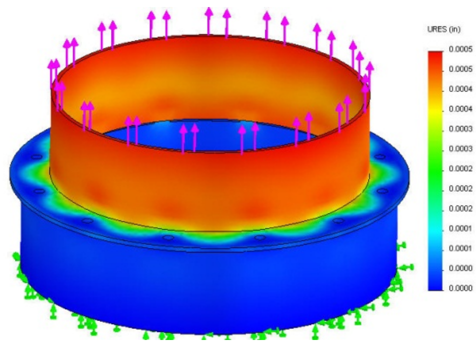
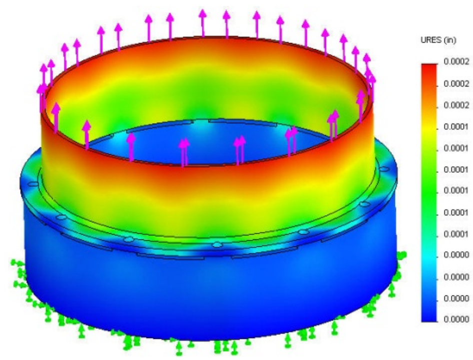
Design	Deflection Plot	Design Notes	Max Deflection Value [in]
		• Flanges too thin • Moment arms too large • No chamfer or fillet	0.0050
		• Thicker flanges • Smaller moment arms, but fits fasteners • Chamfer added for stiffness • No significant increase in mass	0.0002

Table 6-3: Features of adjoining structure[4]

The stiffness of flanges are important relative to overall stack stiffness. If the flange stiffness is too low the first mode lateral frequency of the entire stack can decrease detrimentally. For proper operation of the Lightband, the flanges should be stiff enough to guarantee the preload of the Lightband will not excessively warp the adjoining structure and vice-versa. PSC offers consultation on design of adjoining structures to customers.

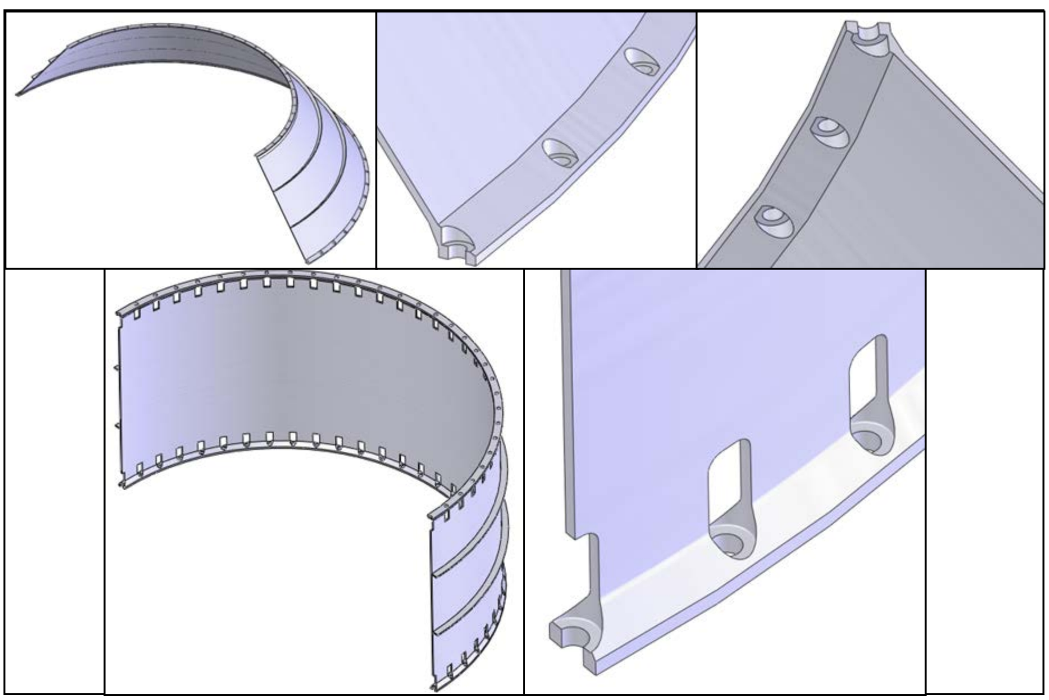
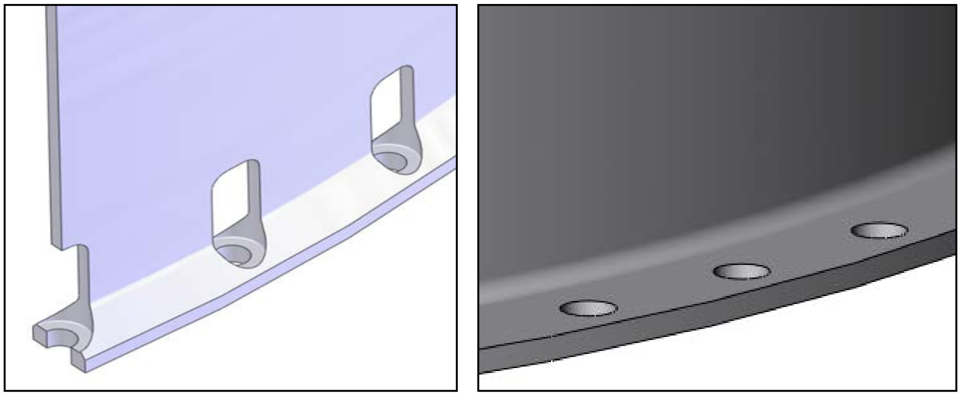


Figure 6-17: Structures with optimal flange design. Moment arms in the flange are minimal, maximizing stiffness and strength

[4] The lower cylinder represents a Lightband. The upper cylinder with flange represents an adjoining structure. The applied load is 1,000 lb. The materials are aluminum.

As noted in Table 5-1, there are two sets of required flatness for adjoining structure values. Though somewhat subjective, if adjoining structures are relatively stiff, the required flatness will be greater than if the adjoining structure is relatively flexible. A relatively flexible structure will conform to the flat interface better than a relatively stiff one. See Figure 6-18. If in doubt about the stiffness of your adjoining structure, please contact PSC.



Stiff

- No moment arm from web to bolt hole
- Bolt holes aligned with structure
- Thick walls relative to bolt diameter
- “I-beam” shape

Flexible

- Moment arm from web to bolt hole
- Bolt holes not aligned with structure
- Thin walls relative to bolt diameter
- “C-Channel” shape

Figure 6-18: Example of stiff and flexible adjoining structures

The type of adjoining structure can also have an effect on operation and integration of the Lightband. Customers should be aware of the effects of their choice of adjoining structure before integration and adequately plan for any likely issues. See Table 6-4.

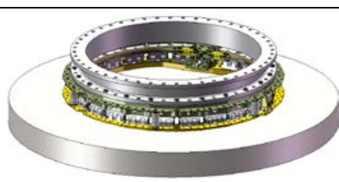
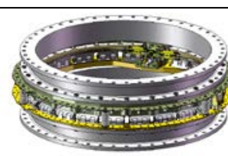
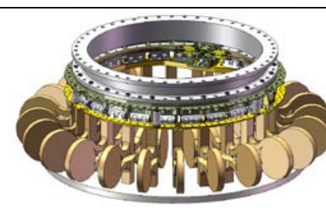
	Lightband Adjoined to...		
	Stiff Weldment, Ring, or Plate	**Transition Rings**	**Isolation System**
Typically Characterized As (See Table 5-1)	Stiff	Flexible	Flexible
Most Similar Type of Flight Adjoining Structure	Adapter plate	Adapter cone or ring	Isolation system
Flatness	Often difficult to manufacture within required flatness tolerances.	Typically meets flatness requirement.	Reduces flatness requirement.
Lightband Flexure	Often too stiff, does not allow Lightband to flex enough during operations.	Allows Lightband to flex nominally and maintains required stiffness during operation.	Provides best chance for successful Lightband integration and operation.
Shimming	Difficult to meet flatness requirements via shimming.	Less difficult to meet flatness requirements via shimming.	Not necessary.
Relative Cost to Manufacture/Procure	Low	Medium	High
Relative Cost to Ensure Manufactured Flatness	High	Medium	N/A
Side View			
Isometric View			

Table 6-4: Comparison of Lightband adjoining structures

6.9 Fasteners to Adjoining Structures

PSC does not provide fasteners to adjoining structures. However, PSC uses MS16996-24 fasteners torqued to 100 +15/-0 in-lb. in acceptance and qualification tests. Exceptions to this torque specification have been made during proof tests in order to prevent bolted joint slipping.[5] Fasteners have never displayed degradation during any test at specified bolt preloads.

¼ inch socket head cap screws with small pattern washers are recommended when fastening from the Upper or Lower Ring to adjoining structures. The through holes in the Upper and Lower Rings are nominally 0.280 inches in diameter. This allows for 0.030 inches of gap between a ¼ inch fastener and the through hole. This is beneficial in the assembly process because fasteners are easier to install, but limits the capacity of fasteners to guarantee alignment of structures to the Lightband.

For 15 inch diameter Lightbands, PSC recommends the use of reduced head diameter ¼-28 socket head cap screws to fasten the Lower Ring to adjoining structures. This prevents the interference between the fasteners and the Leaves described in the Lightband Operating Procedure.[6] The head diameter should be 0.340 inches. See Section 22.

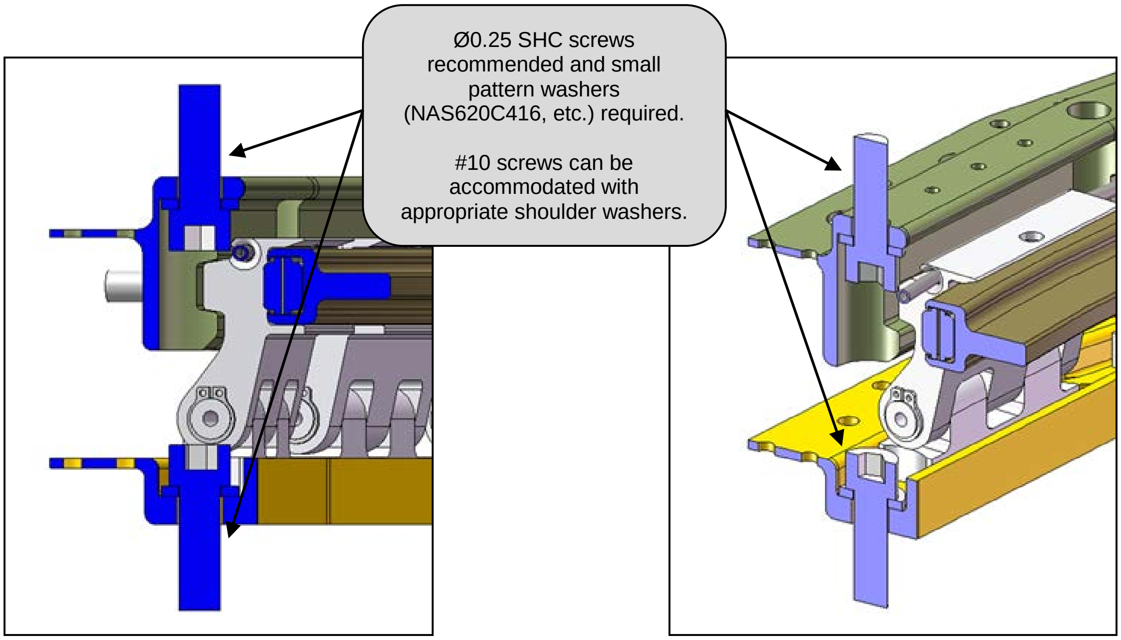


Figure 6-19: 1/4 inch fasteners from Lightband to adjoining structures

Smaller fasteners (such as #10) are also acceptable for use, but must be approved by PSC. Contact PSC to discuss the use of any fastener size other than ¼ inch. Hex head fasteners will not work because there is insufficient room for tools to grip the hex head. Fasteners must be installed at every location in order to integrate the Lightband. Do not skip a bolt as this will substantially decrease strength and stiffness of the Lightband.

The thermal extremes of the bolted joint often drive the selection of fasteners. Users anticipating temperatures beyond +10 to +50°C should examine the pre-load changes associated with coefficient of thermal expansion (CTE) mismatch. In the past, missions on the Space Shuttle have driven bolted joint design to extremes because joints are expected to survive landing loads at very low temperature (-40°C). NASA's NSTS-08307 document outlines a thorough bolted joint analysis.

Stiffness is affected by bolted joints. Generally a greater pre-load leads to greater stiffness.

Ideally, the Lightband should be fastened to adjoining structures when the Lightband is separated. This allows easy access to the fasteners with tools. When the Lightband Rings are mated together, barely sufficient access to fasteners is available from the inside of the Lightband. It is essentially impossible to fasten a mated Lightband to adjoining structures if access to fasteners is only available from the outside of the Lightband.

[5] See PSC Documents 2002319A and 2002512-

[6] See PSC Document 2000781

6.10 Line Load Limits

Line loading in the X_{LB} axis arises from loads in the X_{LB} direction and moments about the Y_{LB} or Z_{LB} axis. Generally, the moments about Y_{LB} and Z_{LB} generate higher line loading than axial loads. In other words, lateral load cases are the limiting factor in strength margin.

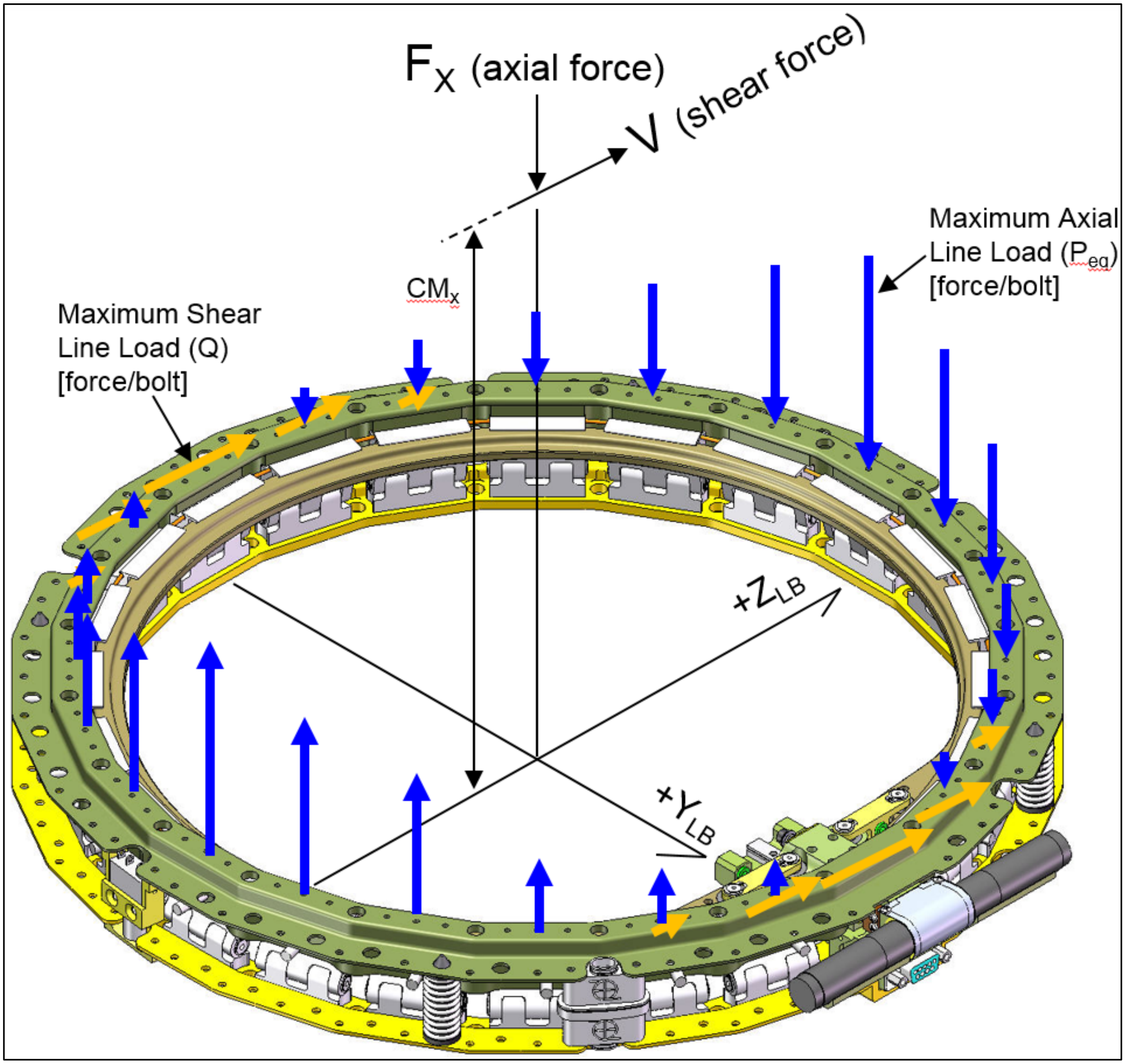


Figure 6-20: Line loading forces

Force per Bolt	Direction	Yield Limit [lbf/bolt]	Ultimate Limit [lbf/bolt]
P_{eq}	X_{LB} (Axial)	1880.0	2256.0
Q	Y_{LB} or Z_{LB} (Shear)	774.0	928.8

Table 6-5: Line load limits[7]

In Table 6-5, the P_{eq} and Q values are conservative as no yield or cracking has ever been detected on a Lightband after test when the line load was below prescribed yield limits. Ultimate limit in the next column is determined by multiplying yield limit by the ratio of ultimate to yield stress for the materials of the Upper Ring (Al-Aly 7075-T7), Lower Ring (Al-Aly 7075-T7), and Leaf Assemblies (Al-Aly 6061-T6). The minimum ratio (1.2) is used as a conservative assumption.[8]

Each Leaf corresponds to through-holes for fastening to the adjoining structures. The through holes are sized for ¼ inch socket head cap screws. PSC analysis and tests have shown that the as-designed fastener hole size and spacing is optimum for Lightband operation. All testing at PSC is performed with ¼ inch fasteners because PSC test cells have ¼-28 accepting threads.

[7] Per PSC Document 2002319 Rev A Lightband Loading Capability Proof Test.
[8] Per PSC Document 2002286 Rev D MkII MLB15.000-24 Analysis.

Axial line loading arises from axial (X_{LB}) and lateral (Y_{LB} or Z_{LB}) loading, whereas shear line loading arises from only lateral (Y_{LB} or Z_{LB}) loading. In flight, lateral loads tend to make the greatest contribution to line loading. Maximum lateral load and axial load do not occur at the same time and standard PSC strength testing reflects this fact.

Note that PSC documentation often expresses line loading in terms of force/Leaf instead of force/bolt. Lightbands naturally have 1 less Leaf than bolt, but it is assumed that the difference in line load value from this computation method is trivial. Thus the terms force/Leaf and force/bolt are interchangeable.

Maximum axial line load is given by Equation 1:

$$\mathrm{P_{eq}} = \frac{\mathrm{F_X}}{\mathrm{n}} + \frac{\mathrm{4VCM_X}}{\mathrm{nD}} \qquad (1)$$

Where:
P_{eq} is maximum axial line loading [force per bolt]
F_X is axial force [force]
n is the number of fasteners in the bolt circle [-] (n is one more than the number of Leaves)
V is lateral force [force]
CM_X is the distance from the Lightband origin to the load application point in the x direction [length]
D is the bolt circle diameter [length]

Maximum shear line loading is given by Equation 2:

$$\mathrm{Q} = \frac{2}{n}\left(V + \frac{M_x}{D}\right) \qquad (2)$$

Where:
Q is the maximum shear line load [force per bolt]
V is the lateral force [force]
n is the number of fasteners in the bolt circle [-] (n is one more than the number of Leaves.)
D is the bolt circle diameter [length]
M_X is the maximum applied torsional moment about the X_{LB} axis (Typically negligible in flight loading.)

The values in Table 6-5 were calculated by applying loads produced by Equation 1 and Equation 2 to a Lightband in strength test. As such, these values incorporate any peaking associated with the discontinuity of the Motor Bracket assembly. Because the Motor Bracket is located in the space of one Leaf Assembly, the distribution of load is discontinuous at the Motor Bracket Assembly. By application of Equation 1, Equation 2 naturally incorporates the load peaking associated with the Motor Bracket Assembly. Therefore an additional peaking factor need not be applied for that purpose.

It is useful to observe that the Lightband behaves structurally like a thin-walled cylinder when stowed. Line loading may peak in areas where stiffness peaks. For example, if a MLB15.000 is installed on a rectangular satellite that has 15 x 15 inch base plate, line loading is expected to peak at the midpoint of the sides because the stiffest region of a satellite is at the midpoints. Engineers should design structures to the maximum allowable line load of the adjoining structures and ideally have a design that minimizes the extremes of line loading. Such a design is also structurally efficient as shown in the cylindrical satellite shape on the right side of Figure 6-21. Bolted joints to adjoining structures should be designed (at a minimum) to react the expected line loads.

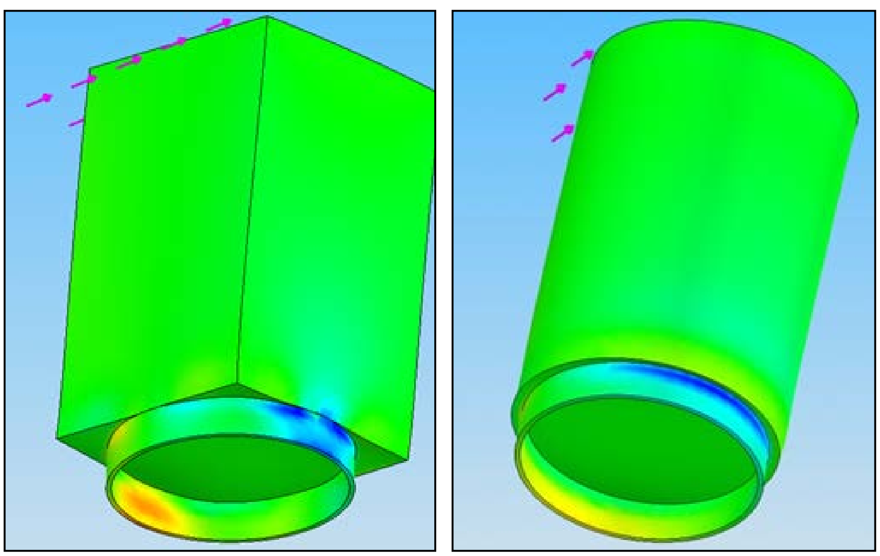


Figure 6-21: A round separation system and a square satellite can create high line loading

6.11 Flatness and Parallelism

Prior to joining to the Lightband, the surfaces adjoining the Lightband should be flat to the specification defined in Table 5-1.

Figure 6-22: A Lightband attached to a launch vehicle cone and CAD model showing resulting stress peaking that occurs when adjoining two warped surfaces

When the adjoining vehicles are extremely warped or surfaces are not parallel, an attempt to join the Lightband to both adjoining structures may simply break the Lightband. Joining a Lightband to only one adjoining structure will generally not increase stress because separation systems are designed to be more flexible than adjoining structures.

It may be tempting to design flexible features to attenuate stress exhibited in the warped structures that are joined. However, this can lead to an unacceptably low stiffness and first mode frequency of the entire system. To achieve both a low stress and high stiffness system, flatness of the adjoining structures must be controlled.

Isolation systems like Moog CSA Engineering's SoftRide intentionally add flexibility to joints to attenuate response. Furthermore, isolation systems offer an additional benefit in the substantial relaxation of adjoining structure flatness requirements.

Finite element models (FEMs) nominally assume perfect flatness of adjoining structures. Therefore, FEMs can obscure this potentially significant reduction in structural margin.

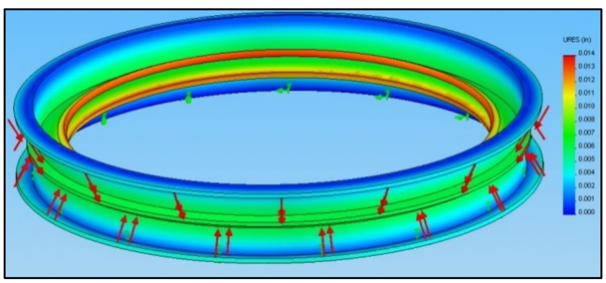


Figure 6-23: FEM simulates a clamp band separation system via radially inward preload from band tension. Warping can result.

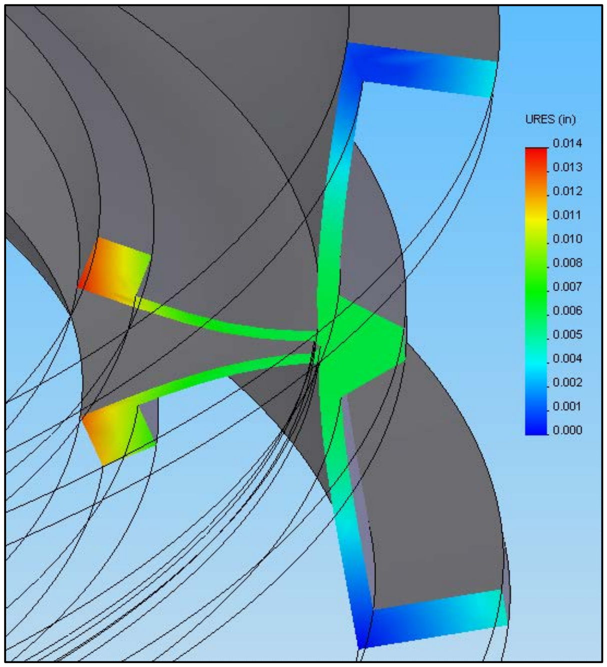


Figure 6-24: A deflection of 0.004 inches at the interface to adjoining structures is created by preload

Lightbands and clamp bands embody the perverse nature of mechanical assembly; not only do they warp in proportion to preload, but a warp applied to them can affect their preload. Critically, as many mechanisms engineers have observed in test, the structural performance (strength and stiffness) is highly correlated to preload. PSC engineers often observe changes in internal strain as structures are joined to the Lightband. A 20% change in preload as the separation system is fastened to an adjoining structure has been observed.

Easily-fabricated structures adjoining separation systems may be expensive to make flat. Alternatively, structures that may be expensive to fabricate can be easy to make flat. For example, a thrust cone that interfaces the final stage engine to the launch vehicle can be easily made by riveting machined rings to conical sheets. The riveting process can stress the thrust cone. This may manifest itself as warping (a lack of flatness) when the riveted structure is removed from its much more rigid tooling. To attain flatness requirements, the riveted structure must be machined or shimmed at additional cost. As a more expensive option, the thrust cone could be directly machined from a conical forging ensuring flatness requirements are met.

Engineers should consider the fact that all manufacturing and joining processes (riveting for assembly, fastening to adjoining structures, curing of composites) increase strain energy and thus will warp structures.

6.12 Damping Ratio

Damping ratio may be used to calculate the response of a structure attached to the Lightband. A greater damping ratio reduces the response of the system at vibratory resonance. To estimate the damping ratio of the Lightband, results of vibration tests of the Lightbands with mass mock-ups attached were used.

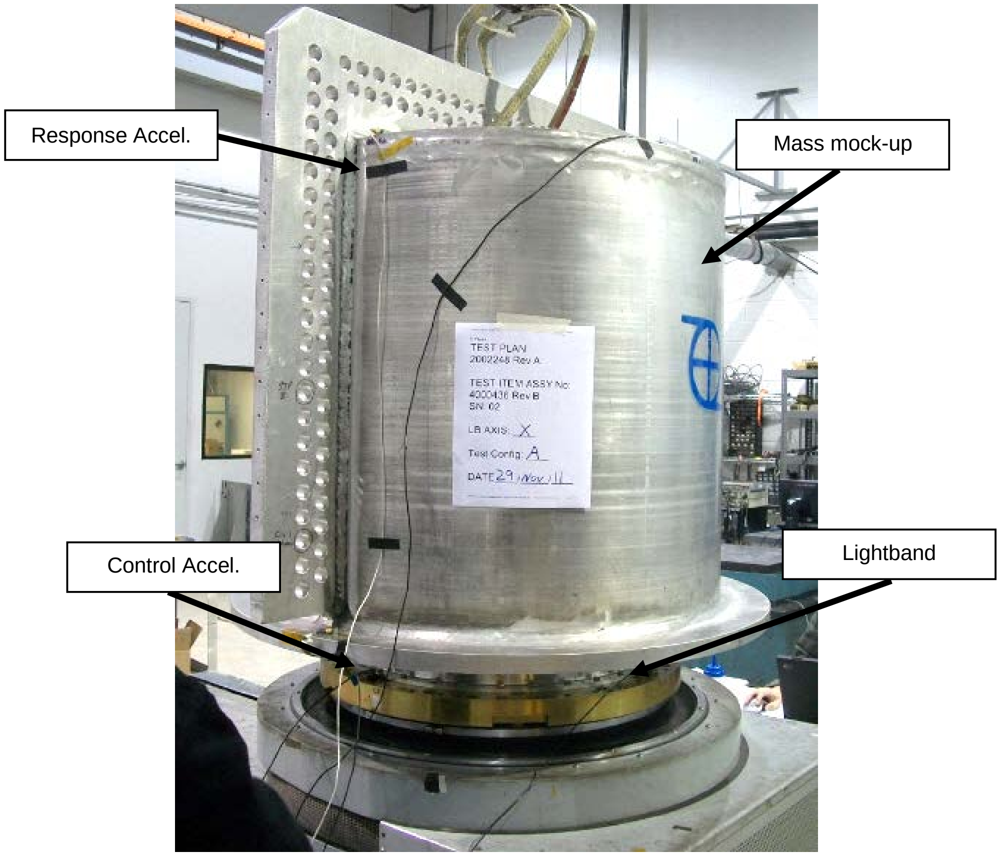


Figure 6-25: Vibration test of a Lightband with a mass mock-up

Since the damping of the mass mock-up and the many bolted joints is included, the measured damping ratio must be higher than the Lightband damping. To arrive at a conservative recommended Lightband damping ratio, the test-measured damping ratios were reduced by 50% as shown in Table 6-6.

	X_{LB}-Axis	Y_{LB}-Axis	Z_{LB}-Axis
Measured damping ratio (d)	0.025	0.069	0.063
Recommended damping ratio (d)	0.013	0.035	0.032

Table 6-6: Damping Ratio

The damping ratio can be calculated if one knows the quality factor, **q**, of a system's response at resonance. Quality factor is the ratio of output response level to the input level. In this case the input and output levels are of the unit gravitational force. The quality factor is defined in Equation 3.

$$q = \frac{1}{2d} \qquad (3)$$

Where:
d is the damping ratio

6.13 SoftRide and Lightband

The SoftRide Isolation System is a spacecraft vibration and shock isolation system designed to reduce launch vehicle-induced loading on the spacecraft. SoftRide is a patented product of Moog CSA Engineering (www.csaengineering.com). It has been flown successfully at least 19 times, including 6 flights with Lightbands (on the XSS-11, TacSat-2, -3, -4, IBEX, FalconSat-3, and GRAIL missions).

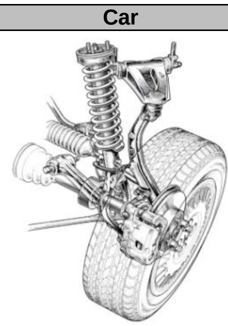
Bicycle	Car	Aircraft	Spacecraft
			

Table 6-7: Valuable payloads are isolated from detrimental external loading using spring-damper (isolation) systems

SoftRide Systems have several benefits when used in conjunction with the Lightband:

1. Substantially reduce flight loads into the payload such as engine transients, random vibration, and shock.
2. Substantially reduce risk by isolating the payload from unanticipated launch load events.
3. Substantially increase damping. SoftRide damping ratio range is 3% to 25% depending on the needs of the mission.
4. Reduce stiffness requirements of the space vehicle because there is less value to a very stiff bus if it is sitting on a very flexible isolation system.
5. Reduce flatness requirements of adjoining vehicles because the isolation system is flexible.
6. Ease integration of the Lightband by eliminating the need to stow the Lightband to join the satellite to the launch vehicle. With the isolation system attached to the already stowed Lightband, integration can occur by simply fastening the launch vehicle to the isolation system.

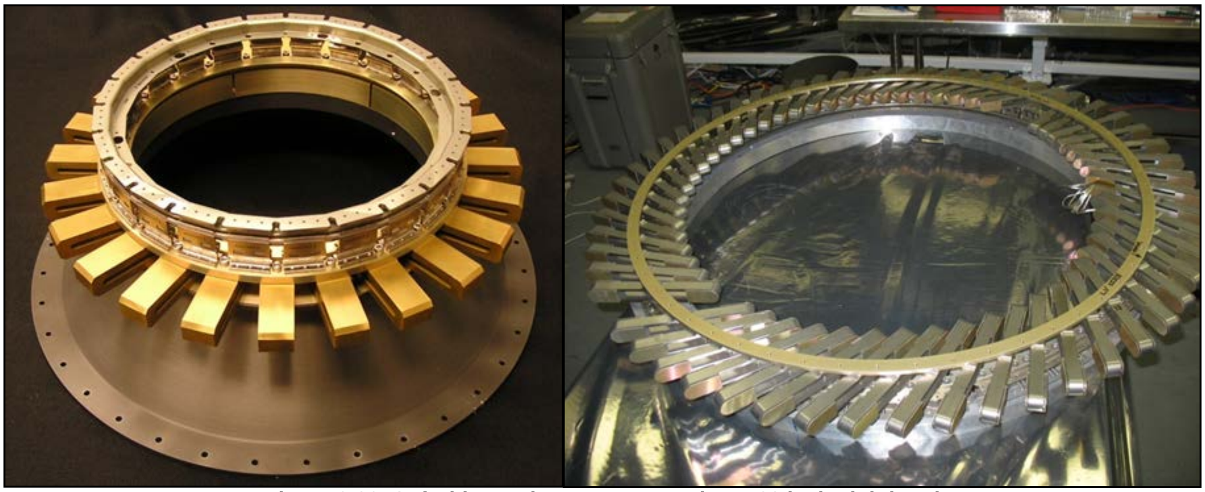


Figure 6-26: SoftRide used on a MLB15 and MLB38 inch Lightband

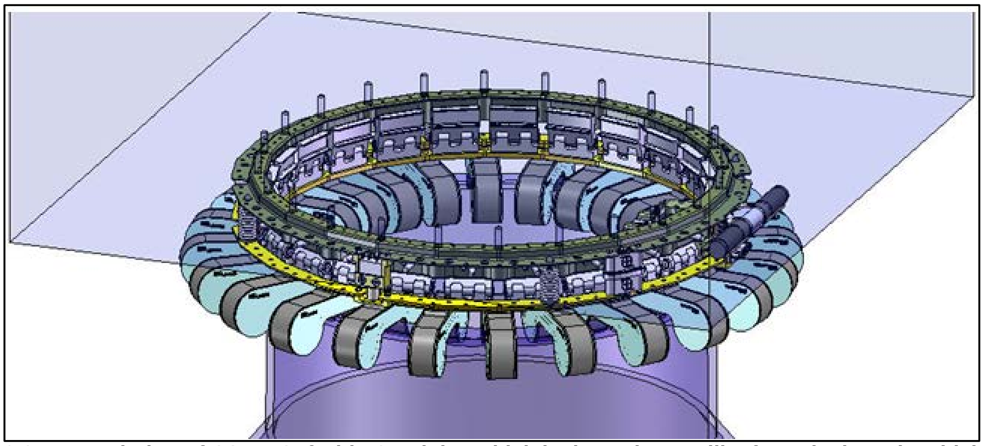


Figure 6-27: A rendering of CSA's SoftRide OmniFlex which isolates the satellite from the launch vehicle loads

Isolation systems add mass that is usually negligible compared to the spacecraft mass. In fact, the mass added by SoftRide is often nullified because the Lightband has a lower mass than other separation systems. Isolation systems require a displacement stroke in order to attenuate dynamic loads. Typical axial strokes in-flight have been in the 0.2 to 0.4 inch range. Lower frequency, higher-performing isolation systems require more stroke than higher frequency isolation systems.

6.14 Fatigue Limits

Fatigue failure is generally defined as failure due to cyclic loading. Fatigue failure is typically manifested in a flight stack as a loss of preload in fasteners, a breakdown of surface treatments at separable interfaces, or cracking of materials. Fatigue can be induced by static loads, sine vibration, random vibration, and shock impulses. It can be locally amplified when dissimilar structures (ex. round to square) are joined to the Lightband. The Lightband's fatigue limit in relation to applied line load is shown in Figure 6-28.

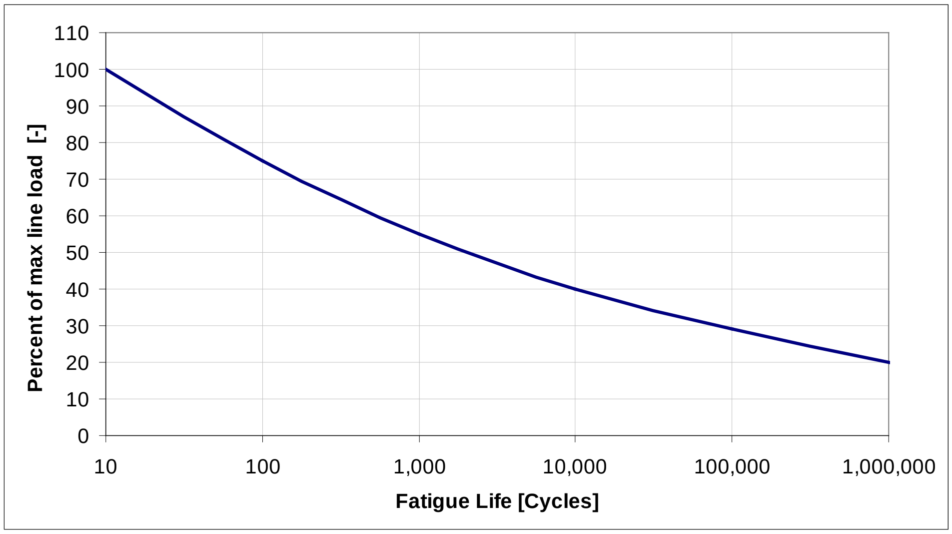


Figure 6-28: Lightband fatigue limits and line loading

6.15 Lifecycle & Refurbishment

The Lightband can be cycled (stow, set-for-flight, & deploy) 60 times before inspection by PSC is required. This includes about 15-20 separation tests that PSC completes prior to shipping to the customer. Thus, the customer may typically separate the Lightband about 40-45 times.

Stowing is more strenuous on the Motor Bracket Assembly than deploying. The Lightband's Motor Assembly consumes about 20 Joules of energy when stowing while it only consumes about 2 Joules when deploying. After the 60th cycle, the Lightband must be inspected by PSC Engineers to determine the wear rate and the amount of lubrication remaining. Using the minimum allowable voltages on all operations maximizes the Lightband's cycle life. Lower voltages produce lower currents meaning stresses in the parts connected to the Motors are minimized. In qualification and development testing, the Lightband has been shown to reliably stow and deploy several hundred times while simultaneously being exposed to extreme temperature cycling (-25 to +90°C).

After a Lightband has been cycled 60 times, it must be inspected by PSC and considered for refurbishment. The typical refurbishment process is as follows[9]:

1) The Lightband is shipped to PSC.
2) Provenance of the Lightband is established. What handling/operation/testing occurred while outside PSC?
3) Analysis of handling and testing is performed to establish potential risks and problem areas. For instance, what line loading was experienced in test?
4) The Lightband is inspected based on Step 3 results. This could be as simple as a visual examination or a complete tear-down and assessment. Only known non-destructive inspection techniques like dye penetrant analysis are performed.
5) A refurbishment plan for the unit based on Step 4 results is created. Examples range from simply re-greasing the Bevel Gears to replacing all components in the load path.
6) The refurbishment plan is executed.
7) A benchtop and environmental testing plan for the refurbished unit is determined. This could be all, none, or a selection of the acceptance tests defined in Section 18 of this document.
8) The environmental testing plan is executed.
9) The Lightband is shipped back to the customer.

6.16 Alignment

<u>Aligning Upper Ring & Lower Ring</u>
Several features act sequentially to guarantee alignment of the Upper and Lower Ring prior to the stow event. In order of operation these features are:

1. The Separation Spring's conical tip mates with the Upper Ring's accepting holes. The telescoping features of the Separation Springs guide for about 0.6 inches of travel.
2. The cut-out for the Motor Bracket Assembly in the Upper Ring only allows one rotary orientation of the Upper Ring.
3. The polymer guide pins in the Separation Connector halves mate together.
4. The shells of the Separation Connector (if attached) align.
5. The shear pins of the Upper Ring and their accepting grooves in the upper link of the Leaves align together.
6. The Leaf lips align with their accepting grooves in the Upper Ring.

It is estimated that the variation in alignment in the above process is about 0.001 inches in any direction

<u>Aligning with adjoining structures</u>
The bolt patterns of the Upper and Lower Rings are concentric to within 0.01 inches when the Lightband is stowed. The rotational tolerance of the Upper and Lower Ring is 0.1 degrees when stowed.

Aligning the Lightband to another structure can be accomplished by using flat head fasteners when the adjoining structure is threaded or gage pins when the adjoining structure has a flange with through holes. A flat head fastener has a conical feature that tends to force alignment.

[9] Source: PSC Document 2002653 Refurbishment Procedure

However, flat head fasteners should not be used to permanently fasten the Lightband to an adjoining structure. A gage pin of 0.281±0.005 inch diameter is the nominal diameter that would form a slip fit to the holes on the Lightband.

6.17 Materials and Surface Treatments

Material surface finish may be used to determine rates of radiative heat transfers and surface charging of the Lightband and attached structures. All materials in the Lightband are low out-gassing as defined by ASTM-E-595: total mass loss (TML) is less than 1.0% and a collected volatile condensable materials (CVCM) is less than 0.1%. All of the materials in the primary load path are highly resistant to stress corrosion cracking (SCC) as defined by MSFC-STD-3029. See Table 6-8.

Item	Component Name	Part Number	Material	In Primary Load Path?	Highly Resistant to SCC (1)	Magnetic?	Surface Finish	Vendor
1	Lower Ring	Varies by diameter	Al-Aly 7075-T7351 per AMS-QQ-A-250/12 or AMS 4078	Y	Y	N	Chem Conv, color gold, per Mil-DTL-5541, Cl 3	PSC
2	Upper Ring	Varies by diameter	Al-Aly 7075-T7351 per AMS-QQ-A-250/12 or AMS 4078	Y	Y	N	Hard Anodize per MIL-A-8625, Type III, Class 1	PSC
3	Lower Hinged Leaf	4000391	Al-Aly 6061-T6 per AMS-QQ-A-250/11	Y	Y	N	Electroless Nickel per AMS-C-26074, Class 4, Grade B	PSC
4	Upper Hinged Leaf	4000392	Al-Aly 6061-T6 per AMS-QQ-A-200/8	Y	Y	N	Electroless Nickel per AMS-C-26074, Class 4, Grade B	PSC
5	Hinged Leaf Pin	4000369	Al-Aly 6061-T6 per AMS-QQ-A-250/11	Y	Y	N	Electroless Nickel per AMS-C-26074, Class 4, Grade B	PSC
6	Leaf Retaining Ring	Proprietary	PH 15-7 Mo Stainless Steel	N	-	Y	-	varies
7	Retaining Ring	Varies by diameter	Al-Aly 6061-T6 per AMS-QQ-A-250/11	N	-	N	Hard Anodize per Mil-A-8625 Type III, Class 1	PSC
8	Motor Bracket	4000394	Al-Aly 6061-T6 per AMS-QQ-A-250/11	N	-	N	Hard Anodize per Mil-A-8625, Type III, Class 1	PSC
9	Sliding Tube	4000395	Al-Aly 7075-T7351 per AMS-QQ-A-250/12	N	-	N	Hard Anodize per Mil-A-8625, Type III, Class 1	PSC
10	Link Pin	4000496	A-286 per AMS 5732 or 5737	N	-	N	Passivate per AMS-QQ-P-35 Type II	PSC
11	Ball Screw	Proprietary	Alloy Steel or 17-4 PH Stainless Steel	N	-	Y	-	Proprietary
12	Rail	4000493	400 Series Stainless Steel	N	-	Y	-	Proprietary
13	Ball Nut	Proprietary	Alloy Steel or 17-4 PH Stainless Steel	N	-	Y	-	Proprietary
14	Bevel Gear	4000494	300 Series Stainless Steel	N	-	N	-	Proprietary
15	Bevel Gear	4000495	464 Brass	N	-	N	-	Proprietary
16	Motor Support	4000509	Al-Aly 6061-T6 per AMS-QQ-A-250/11	N	-	N	Hard Anodize per Mil-A-8625, Type III, Class 1	PSC
17	Motor	4000529	Al, SST, Cu, Delrin, Neodymium	N	-	Y	Black anodize	Maxon
18	Spherical Plain Bearing	Proprietary	Carbon Chromium Steel	N	-	Y	MoS2	Proprietary
19	Link	4000434	Al 7075-T7351 per AMS-QQ-A-250/12	N	-	N	Chem Conv, color gold, per Mil-DTL-5541, Cl 3	PSC
20	Link Retaining Ring	Proprietary	PH 15-7 Mo Stainless Steel	N	-	Y	-	varies
21	Gear Cover	4000440	300 Series Stainless Steel	N	-	N	-	PSC
22	Stow End Plate	4000491	Al-Aly 7075-T7351 per AMS-QQ-A-250/12	N	-	N	Chem Conv, color gold, per Mil-DTL-5541, Cl 3	PSC
23	Deploy End Plate	4000492	Al-Aly 7075-T7351 per AMS-QQ-A-250/12	N	-	N	Chem Conv, color gold, per Mil-DTL-5541, Cl 3	PSC
24	Limit Switches	Proprietary	Valox 420 Phenolic, SST, Silver	N	-	N	-	Honeywell
25	Link Plug	4000443	Viton Rubber	N	-	N	-	PSC
26	Linear Way	Proprietary	300 & 400 Series Stainless, 440C	N	-	Y	-	Proprietary
27	Angular Contact Bearing	Proprietary	400 Series Stainless	N	-	Y	-	Proprietary
28	Assorted Shims	varies	Stainless Steel, Steel	N	-	Y	-	Proprietary
29	Wire	M22759/33-22-9	Cu coated Silver w/ PTFE	N	-	N	-	varies
30	Spring Plunger	Proprietary	300 Series Stainless & Delrin	N	-	Y	-	Vlier
31	Ring Roller	4000398	Al 6061-T6 per AMS-QQ-A-200/8 or 225/8	N	-	N	Hard Anodize per Mil-A-8625 Type III, Class 1	PSC
32	Leaf Shear Pin	Proprietary	18-8 Stainless Steel	Y	-	Y	-	McMasterCarr
33	Separation Spring	4000307	300 Series Stainless & Delrin	N	-	N	-	PSC
34	Separation Connector	4000106 & 4000107	Al-Aly 6061-T6 per AMS-QQ-A-250/11, Vespel SP-1, BeCu	N	-	N	Electroless Nickel per AMS-C-26074, Class 4, Grade B	PSC
35	Separation Switch	4000383	Al-Aly, Stainless Steel, Gold	N	-	N	Chem Conv, color gold, per Mil-DTL-5541, Cl 3	PSC
36	Roller Spring	Proprietary	300 Series Stainless Steel	N	-	Y	-	Proprietary
37	Roller Spring Base	4000426	300 Series Stainless Steel	N	-	N	Passivate per AMS-QQ-P-35 Type II	PSC
38	Roller Spring Slider	4000427	300 Series Stainless Steel	N	-	N	Passivate per AMS-QQ-P-35 Type II	PSC
39	Leaf Fasteners	Proprietary	A-286	Y	-	N	-	varies
40	Assorted Fasteners	-	A-286, 300 Stainless, Alloy Steel	N	-	N	-	varies
41	9 Pin Connector	HDC9S2000S	Bronze, Stainless, Glass Filled DAP, Gold	N	-	N	-	Positronic Ind.
42	Leaf Retaining Cord	4000629	302 Stainless Steel per AMS 5688	N	-	N	-	PSC
43	Staking Compound	Arathane 5753 A/B (LV)	-	N	-	N	-	Huntsmann
44	Vacuum Grease	Braycote 601EF	-	N	-	N	-	Castrol
45	Dry Lubricant	-	Molybdenum Disulfide Powder	N	-	N	-	varies

(1) Per MSFC-STD-3029

Table 6-8: Lightband materials and surface treatments[10]

[10] Source: PSC Document 2000849A MLB Materials and Surface Finish List

6.18 Part Marking

Each Lightband is marked with its assembly number, serial number, and coordinate system on both Upper and Lower Rings. PSC does not provide customer-specified part marking, tagging, or bagging.

6.19 Subsystem Weights

Subsystem	PSC part number	Unit Weight [lb.]	Remark	Graphic
Upper Separation Connector	4000107	0.025	The Upper Connector may be placed on either the Upper or the Lower Ring of the Lightband. Includes mounting hardware. See PSC Document 2001025.	
Lower Separation Connector	4000106	0.025	See above.	
Separation Spring	4000307	0.032	Includes mounting hardware.	
Separation Switch main body	4000383	0.039	Includes mounting hardware. See PSC Document 2002204.	
Separation Switch bracket	4000383	0.006	The bracket reacts the force of the plunger. Includes mounting hardware.	
Roll Bracket Assembly	4000585	0.090	Induces rotation about X_{LB} axis. Includes mounting hardware.	
Lightband Compression Tool Assembly	4000637	0.010 (each, not per pair)	Suggested quantity is 1 pair per Separation Spring. Includes mounting hardware. Does not include tie wrap.	

Table 6-9: Subsystem Weights

6.20 Component Spring Parameters

Several Lightband subsystems contain springs that effect separation velocity. Extensive testing has shown about 90 percent of the spring energy shown in the table below is available to create separation velocity. It is assumed that the remaining 10 percent of stored energy is converted to heat from the effect of sliding friction during the separation event.

Spring	Spring Constant [N/mm]	Stroke [mm]	Force Before Separation [N]	Force After Separation [N]	Stored Energy [J]	Remark	Graphic
Separation Spring	4.08	21.64	88.29	0.00	1.02 (±10%)[11]	Used to create the separation velocity. Has telescoping features. PSC PNs 2001071 and 2001065	
Spring Plunger	11.4	3.18	48.8	12.8	0.06	These springs push the Leaves out of the Upper Ring. They do not influence separation velocity. Typically one spring plunger is used per Leaf Assembly.	
Separation Connector	1.9	3.30	12.4	6.2	0.01 (total of all pins)	Data for mated pair. Each connector has 15 spring plunger contacts	
Separation Switch	3.3	3.84	16.5	3.9	0.02	Each Switch houses one spring plunger.	

Table 6-10: Spring parameters

[11]Source PSC document 2001071: Monte Carlo analysis was used to determine this tolerance. It includes variations in stiffness, spring dimensions and assembly dimensions. This variation is eliminated by virtue of measurement of kinetic energy during separation reliability testing.

6.21 Rotation Rates, Separation Velocity, and Separation Springs

Rotation rates are induced by the distance between the CM and the center of the spring force. Rotation rates may be about any axis of a space vehicle as a result of the separation event. For standard Lightbands, the nominal rotation rate requirement is 0.0±1.0 degree per second per axis.

When the sum of the Separation Spring force is not acting through the center of mass of the adjoining structure, rotation rates will result. Rotation rates can be estimated via Equation 4. There are many variables that contribute to this rate and several simplifying assumptions have been made to compensate. Equation 4 assumes the adjoining vehicle is many times more massive (>10X) and has many times more inertia (>10x) than the separating vehicle. It also assumes the pre-separation rates are all zero. Only Separation Reliability testing can produce verifiable values for rotation rates. See Section 18.1.3.

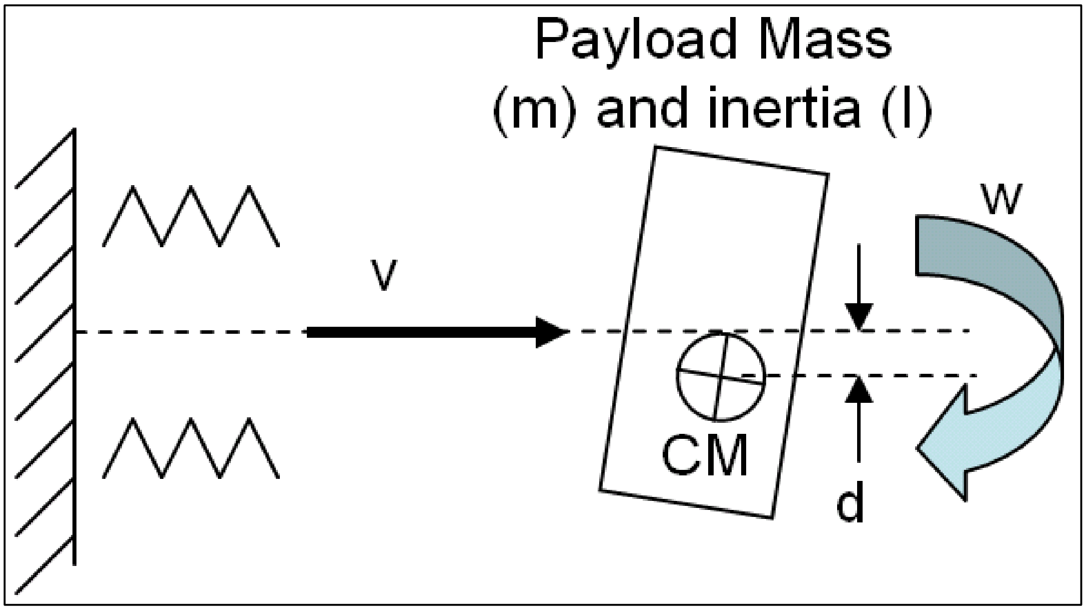


Figure 6-29: CM offset and rotation rate

$$w = \frac{mvd}{I} \qquad (4)$$

Where:
w is the rotation rate [angle per unit time]
m is the mass of the payload
v is the relative velocity
d is the distance between the CM and the resultant location of the Separation Springs
I is the mass moment of inertia about the center of mass of the separating vehicle.

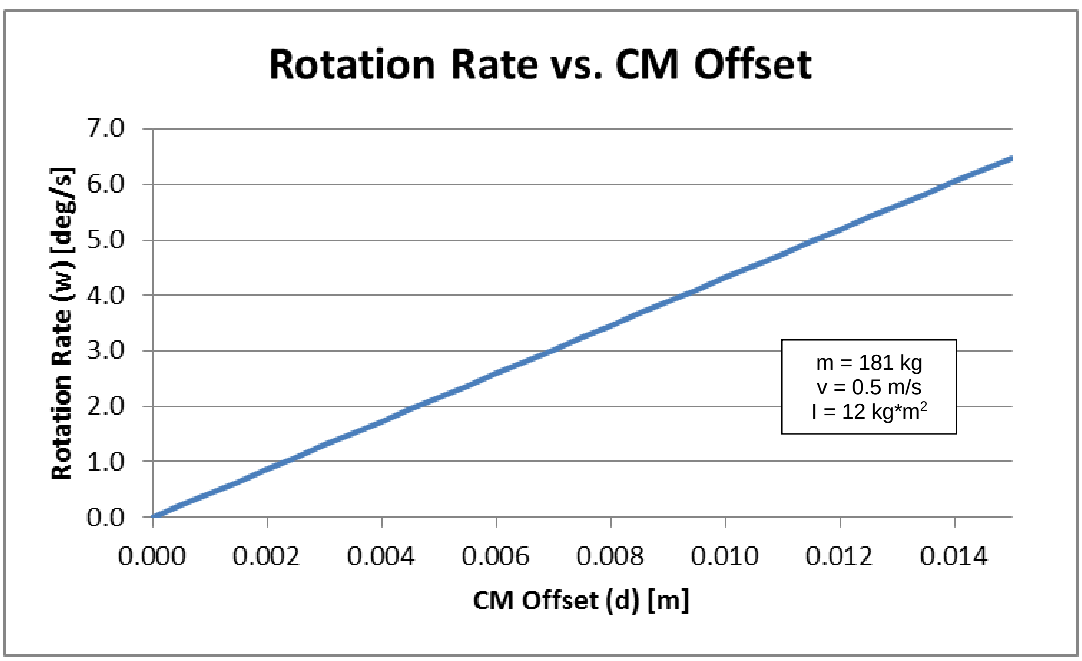


Figure 6-30: An illustration of Equation 4

The Separation Spring configuration may be adjusted on the Lightband so the Springs, as a sum, act through the CM. However it may be easier to move the CM. The lower the **v** required, the lower the rotation rates of the payload.

Sometimes rotation rates are desired as this may beneficially produce even solar heating, dynamically stabilize the vehicle, or counter pre-separation rates. In such cases, relocating the Separation Springs to one side of the CM or allowing the CM offset (**d**) to be significant affects the desired rotation rates.

Equation 5 is used to calculate separation velocity and Equation 6 is used to calculate the number of Separation Springs required given a desired velocity between the payload and the final stage.

$$v = \left(\frac{2nES(m+M)}{mM}\right)^{1/2} \qquad (5)$$

$$S = \frac{mM}{m+M} \times \frac{v^2}{2nE} \qquad (6)$$

Where:
S is the number of Separation Springs required
m is payload mass
M is final stage mass
v is the relative velocity between m and M (ΔV)
n is the efficiency (kinetic energy after separation/stored strain energy before separation)
E is the stored potential energy of a Separation Spring that is converted to kinetic energy manifested as **v**.

The efficiency term ‘**n**’ accounts for the losses in the Lightband during separation. Testing at PSC has shown **n** = 0.90 ± 0.03.

The stored potential energy of a Separation Spring term is a constant for PSC-produced Springs. Previous testing has shown that **E** = 1.02 ± 0.10 J.

Observe that as **v** increases, the quantity of and mass from Separation Springs increases with the square of the kinetic energy after separation. The allowable quantity of Separation Springs varies by Lightband diameter. See Table 5-1. The minimum number of Separation Springs should be six (6) regardless of Lightband diameter to assure reliable separation.

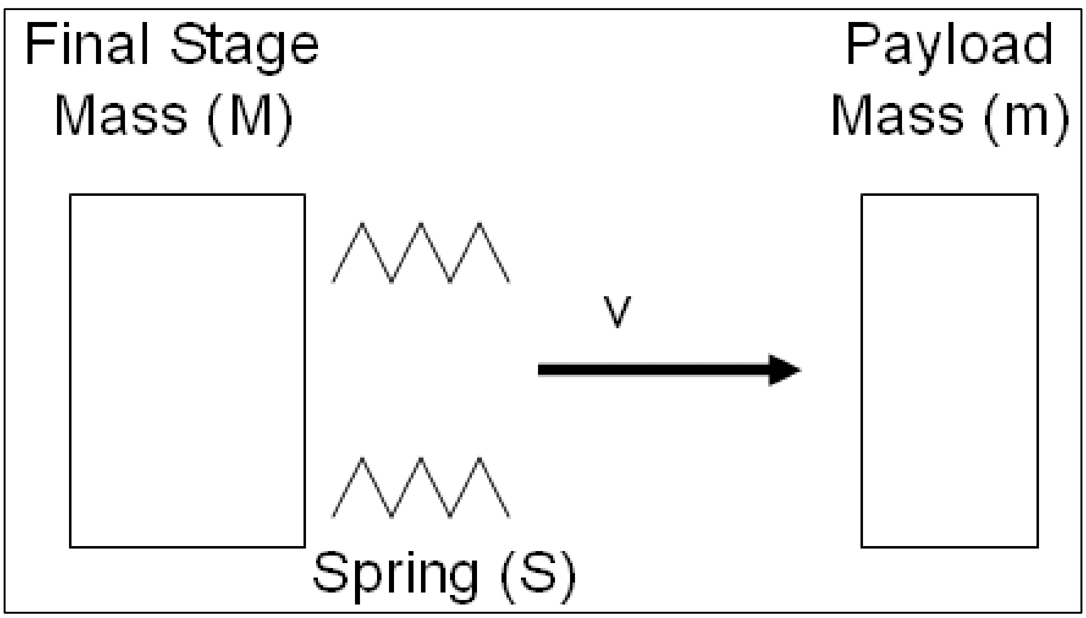


Figure 6-31: The relative velocity, v, is created by the Separation Springs (S)

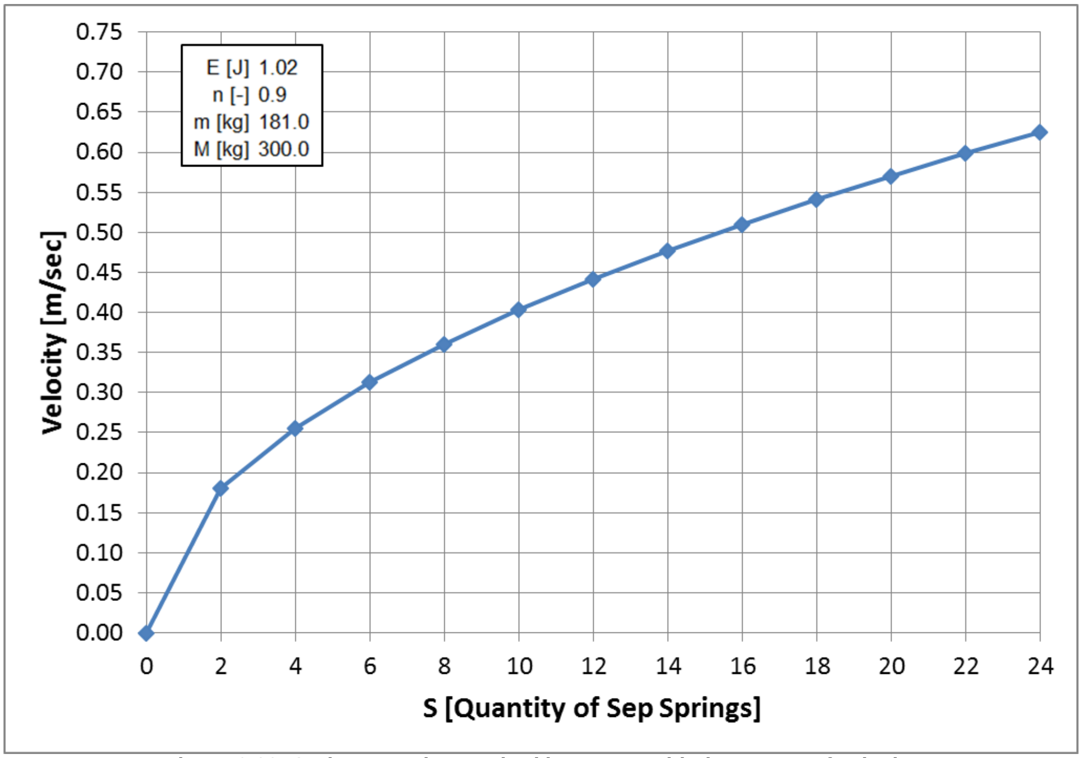


Figure 6-32: Spring quantity required increases with the square of velocity

The location of Separation Springs, Connectors, and Switches need not be symmetric to minimize rotation rates. Sometimes PSC engineers will modify the location (configuration) of Separation Springs to null out rotation rate torques during Separation Reliability tests. This tuning process is done when flight hardware is acceptance tested. See Section 18.1.3. This testing is performed on all flight Lightbands.

When several payloads are on the same launch vehicle, engineers can minimize the possibility of re-contact by varying the separation velocity and direction. Angling the payloads so they push through the center of mass reduces rotation rate torques and the possibility of re-contact. See Figure 6-33.

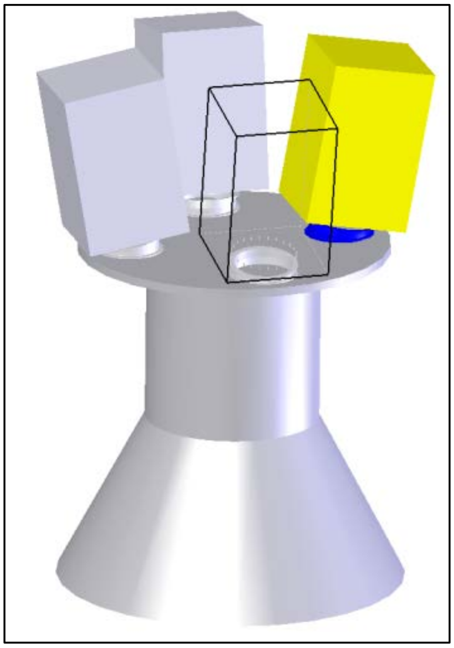


Figure 6-33: Simulated view of several payloads on the same launch vehicle

7. Electrical Properties

7.1 Schematics

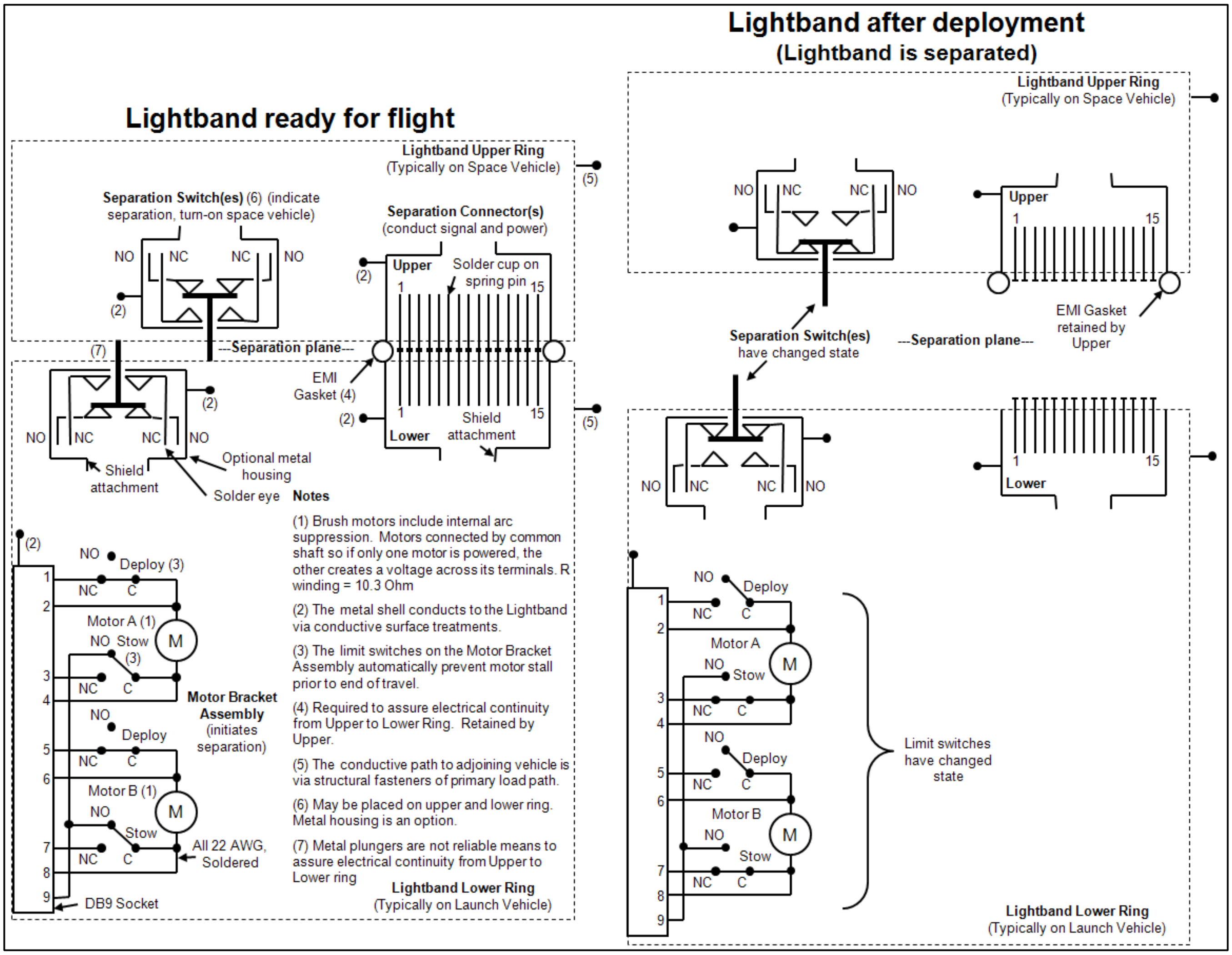


Figure 7-1: Lightband Schematic[12]

[12] The DB-9 connector and the Motor cases are electrically grounded to the Lower Ring.

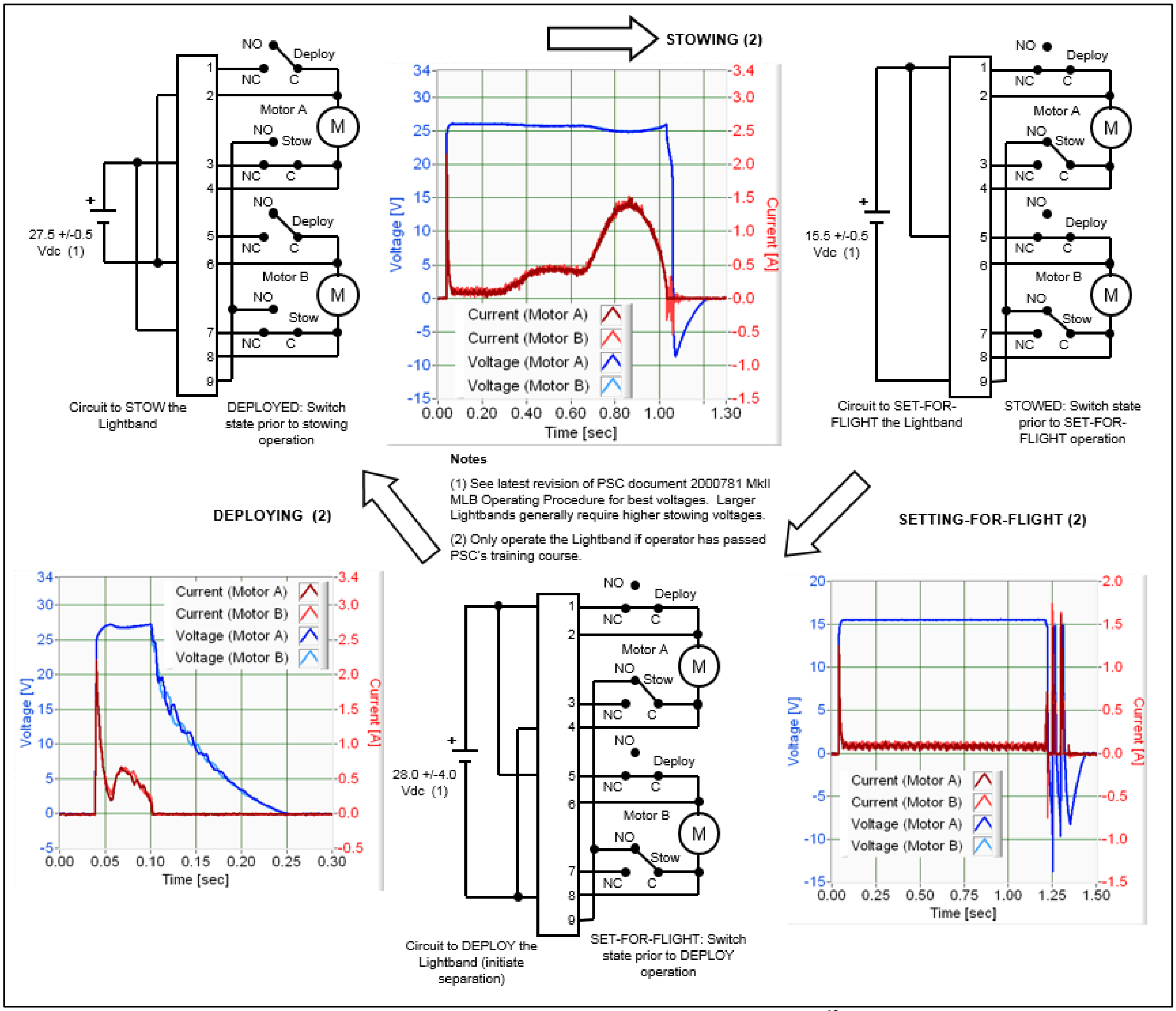


Figure 7-2: Schematics to stow, set-for-flight and deploy[13]

7.2 The Motor Bracket Assembly

The Motor Bracket Assembly is the initiator of the Lightband. Providing it with sufficient power will cause separation of the Lightband when the Lightband is stowed. The DB-9 socket connector is permanently fastened to the Motor Bracket Assembly.

The Motors are DC brush (precious metal commutation). They contain permanent magnets. The manufacturer is Maxon Motors US and the part number is RE16-118686. A version of this motor is used to operate the Martian Rover “Sojourner”.

The Motors are physically connected to each other via bevel gears. Both should be simultaneously powered to induce Lightband separation. However, one motor alone will power the Lightband to cause separation as a redundancy mechanism.

Stowing the Lightband shall only be performed by powering both Motors because the stowing process requires more power than a single Motor can provide. Beneficially, if the Lightband can’t be stowed, this indicates a fault in the Motor Bracket Assembly. If it can be stowed, this indicates the Motor Bracket Assembly is functional.

Maximum reliability of the Lightband can be attained by minimizing the power into the Lightband and the number of cycles. Specifically, avoid unnecessary stow and deploy operations and minimize specified voltage levels. Higher voltages will put more power into the mechanism. More power leads to higher current which leads to higher torque which leads to higher stresses in the Motor Bracket Assembly.

[13] Source: PSC Document 4000697B

7.3 Wiring Harness Design

In the beginning of programs, engineers and program managers often underestimate the cost, weight, and size of wiring harnesses. This is due in part to the difficulty of modeling a harness using CAD software. Harnesses sometimes cost and weigh more than the Lightband. Additionally, poorly-designed harnessed can obstruct access to the Lightband fasteners. If the net shape of the harness is not predetermined, it may not fit and will require extensive re-work. As such it is **absolutely essential** to complete a detailed CAD model of the wiring harness. PSC does not supply harnesses from the Lightband or through the Lightband. PSC recommends the simplest possible harness design using the smallest quantity of Separation Connectors and switches.

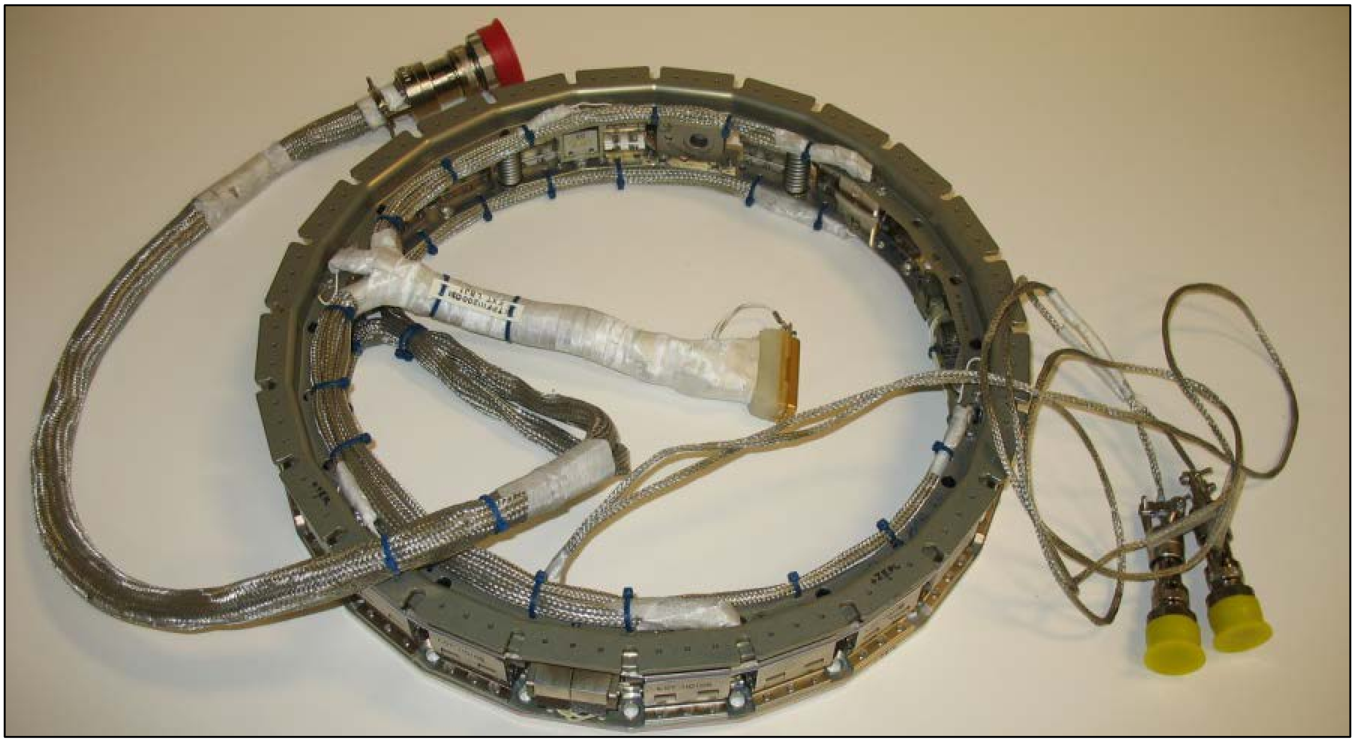


Figure 7-3: A fully featured 3.0 lb. harness on a 5.2 lb. separation system

Users should anticipate the process of attaching the harness to the halves of the Lightband and the adjoining vehicles. The harness can be attached or removed from the Lightband in both the stowed and deployed states. The Separation Connectors and Switches are designed to be attached to the Lightband from the outside of the ring while deployed, but can also be installed when stowed. While the harness can be passed through the Leaves in the Lower Ring assembly of the Lightband, doing so creates a substantial mechanical integration difficulty. Getting tools at the fasteners to adjoining vehicles becomes difficult or impossible. Internal harnesses should be avoided because of this access issue.

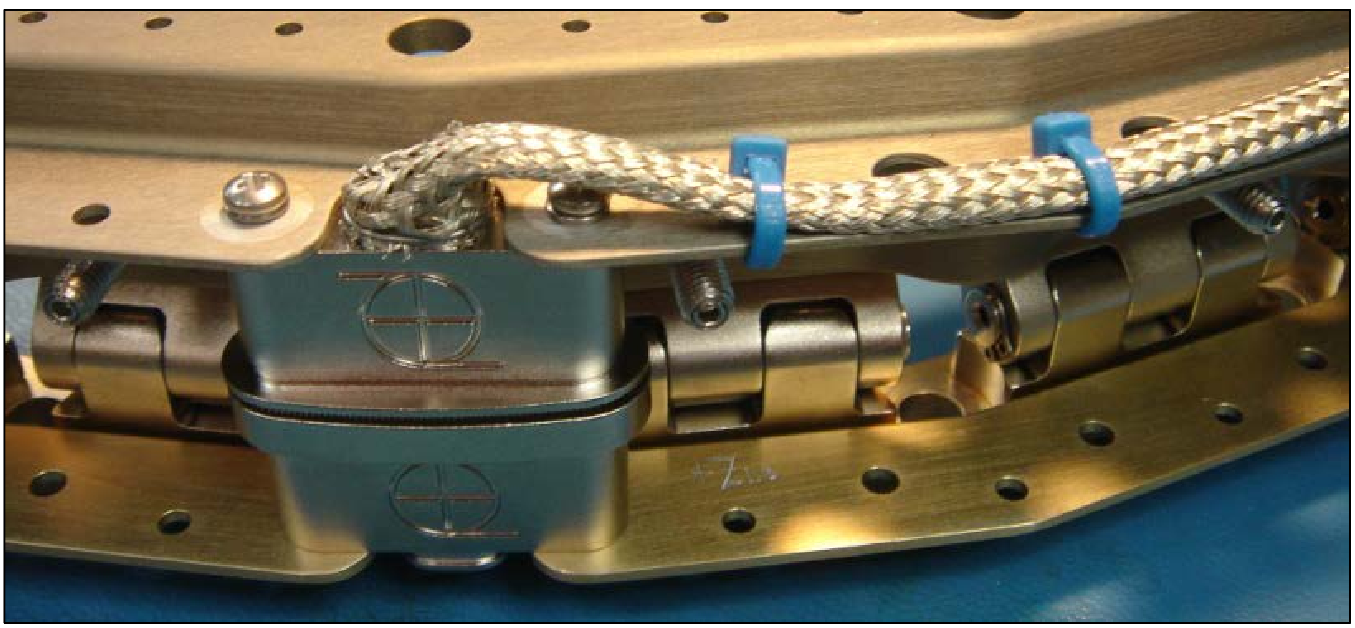


Figure 7-4: Through-holes on the outer lip of the Lightband Upper and Lower Ring exist for routing tie wraps to support harnesses

7.4 Separation Electrical Connectors

The Separation Connector is designed by PSC exhibits essentially zero friction during separation so as to ensure low rotation rates. Most electrical connections are designed to stay together, an attribute separation systems must avoid! A full description of PSC's Separation Connectors can be found in PSC Document *2001025 Separation Connector Data Sheet.*

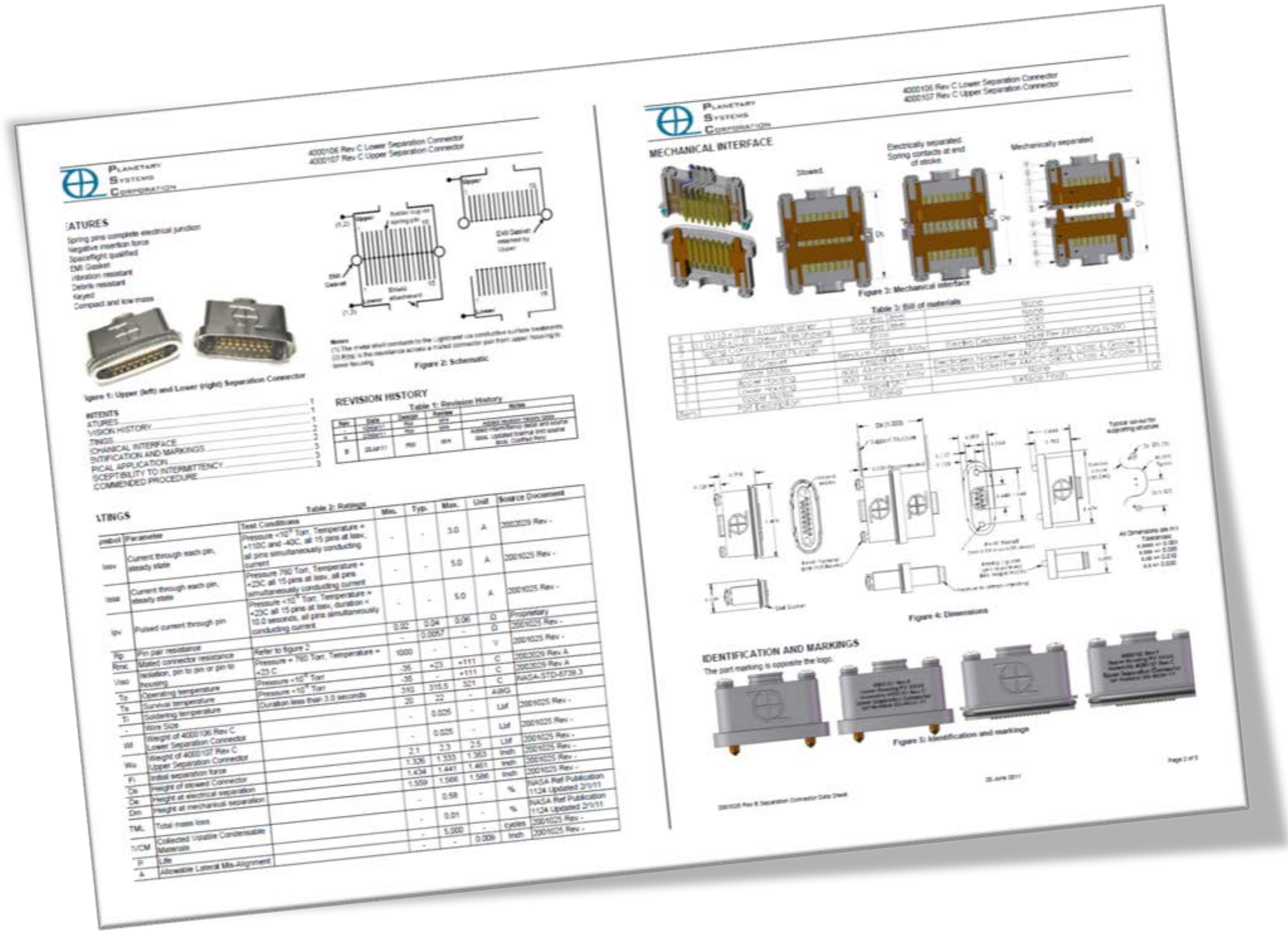


Figure 7-5: Separation Connector as described in PSC Document *2001025 Separation Connector Data Sheet*

The connectors have been extensively tested in shock, vibration, and thermal vacuum environments. Product benefits include:

- Prevents incorrect Lightband alignment via a keying feature.
- Separates in parallel with the Lightband to ensure minimal induced rotation.
- Can ship ahead of the Lightband and allow the harness to be manufactured concurrently by the customer. In such a case, the harness may be attached to the Lightband whenever convenient for the customer. The Connectors can also ship with the Lightband if desired by the customer.

Occasionally, Lightband users desire to employ PSC Separation Connectors as used as electrical loop-backs. This should be done with caution as the junction can be intermittent during very high shock and vibration. Employing redundancy and de-bounce into the circuits has been shown to alleviate this concern. Alternatively, Separation Switches may be employed instead of loop-backs.

7.5 Separation Switches

The Separation Switch is designed by PSC and may be attached to the Upper or the Lower Ring. It is used to communicate the separation event to either adjoining vehicle. A full description of PSC's Separation Switch can be found in PSC Document *2002204 Separation Switch Data Sheet.*

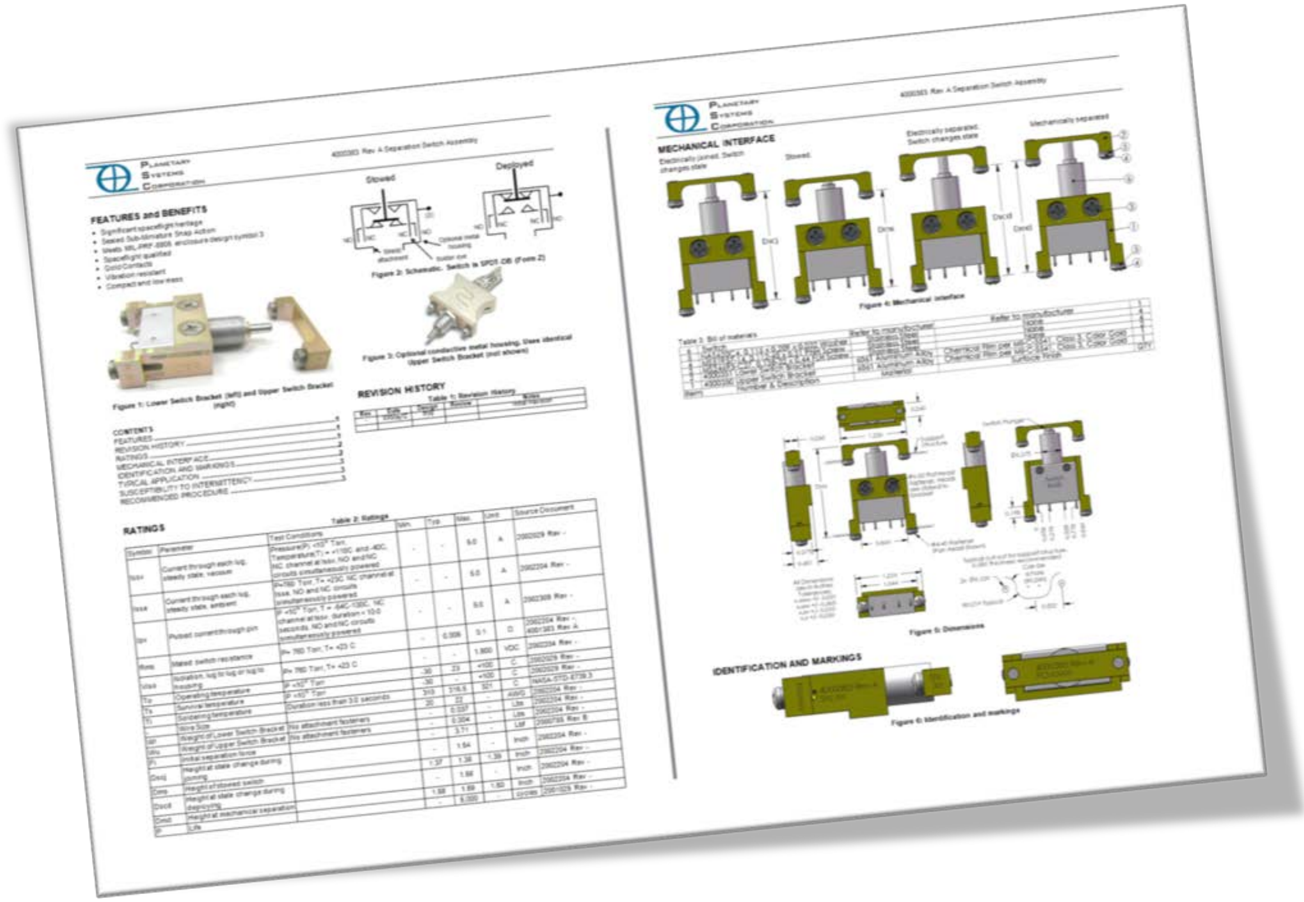


Figure 7-6: Separation Switch as described in PSC Document *2002204 Separation Switch Data Sheet*

During a past vibration test performed by PSC, intermittencies were detected on circuits through the Switches at random vibration levels of 17 G_{rms}. During this test, the vibration spectrum was biased towards high frequency. In the case where users anticipate operating in an extreme environment, de-bounce circuitry in the electrical path may be useful.

7.6 Operation Electrical Parameters

Allowable electrical parameters and schematics for all three Lightband operations can be found in the latest version of PSC Document *2000781 Lightband Operating Procedure* which is available for download on PSC's website.

Skipping the set-for-flight operation and deploying the Lightband from a stowed state is not recommended. If the set-for-flight operation is skipped, the Lightband will require approximately 0.65 seconds to initiate. Additionally, the time to initiate results will be less consistent over multiple deployments without a set-for-flight operation. Further detail is available in PSC Document *2000901 Vibration Qualification Test of Motor Bracket Assembly*.

Motors are not only the means to initiate separation, but outstanding transducers that provide great insight into the state of the Lightband. Power (voltage multiplied by current), energy (integral of power) and torque (torque constant multiplied by current) can easily be calculated via motor response data. When necessary, this gives engineers a thorough understanding of Lightband performance.

Note Regarding Current Values

The first peak current parameter defined in 2000781 occurs when a motor is turned on. First peak current is calculated via Equation 7 (Ohm's Law) where I is the current in amperes, V is the voltage in Volts, and R is the motor winding resistance in Ohms. When the motor is turned on, the current rises to V/R for no more than 0.02 seconds. The winding resistance of the Motors is 10.3 Ω. However, R varies with temperature, T, in accordance with Equation 8[14] .

$$\mathrm{I} = \frac{V}{R} \qquad (7)$$

$$\mathrm{R} = 10.3\big(1 + 0.0039(T - 25)\big) \qquad (8)$$

[14] Source: Manufacturer specifications

7.7 Separation Parameter Variation

The following figures are used to illustrate how a Lightband's time to initiate varies with both voltage and temperature.

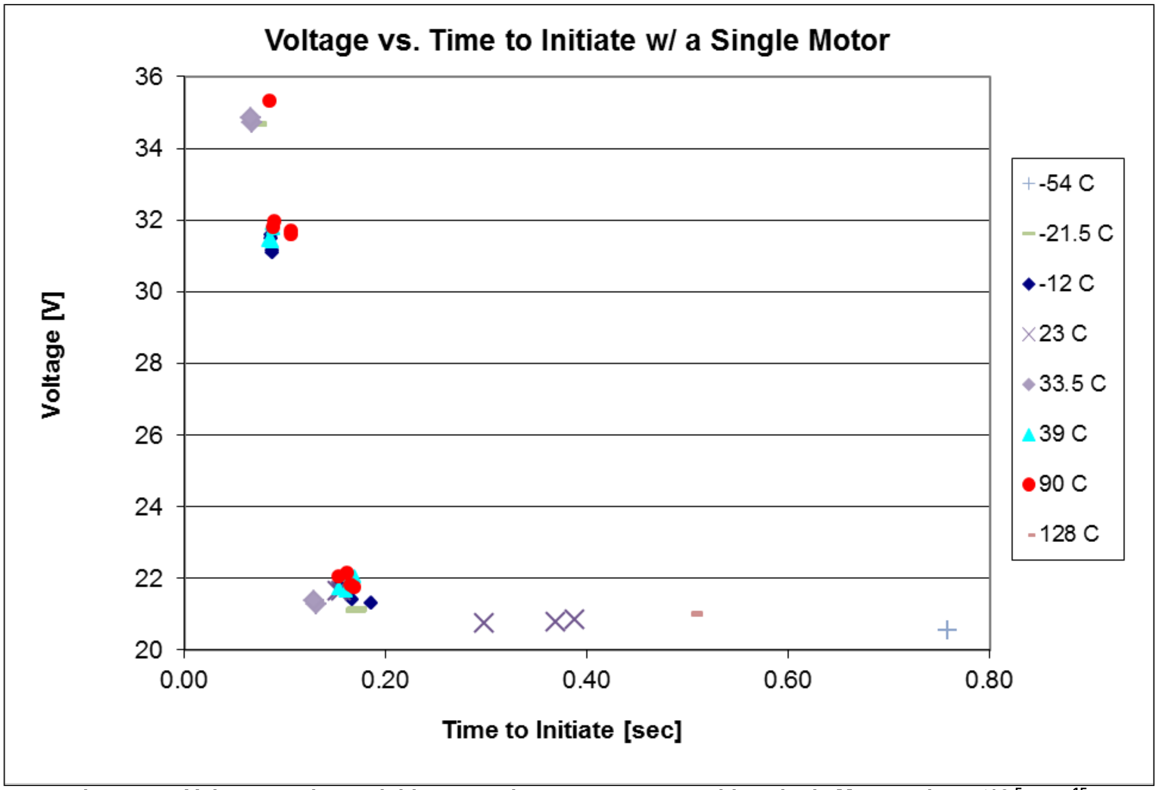


Figure 7-7: Voltage vs. time to initiate at various temperatures with a single Motor only at ≤10^{-5} Torr[15]

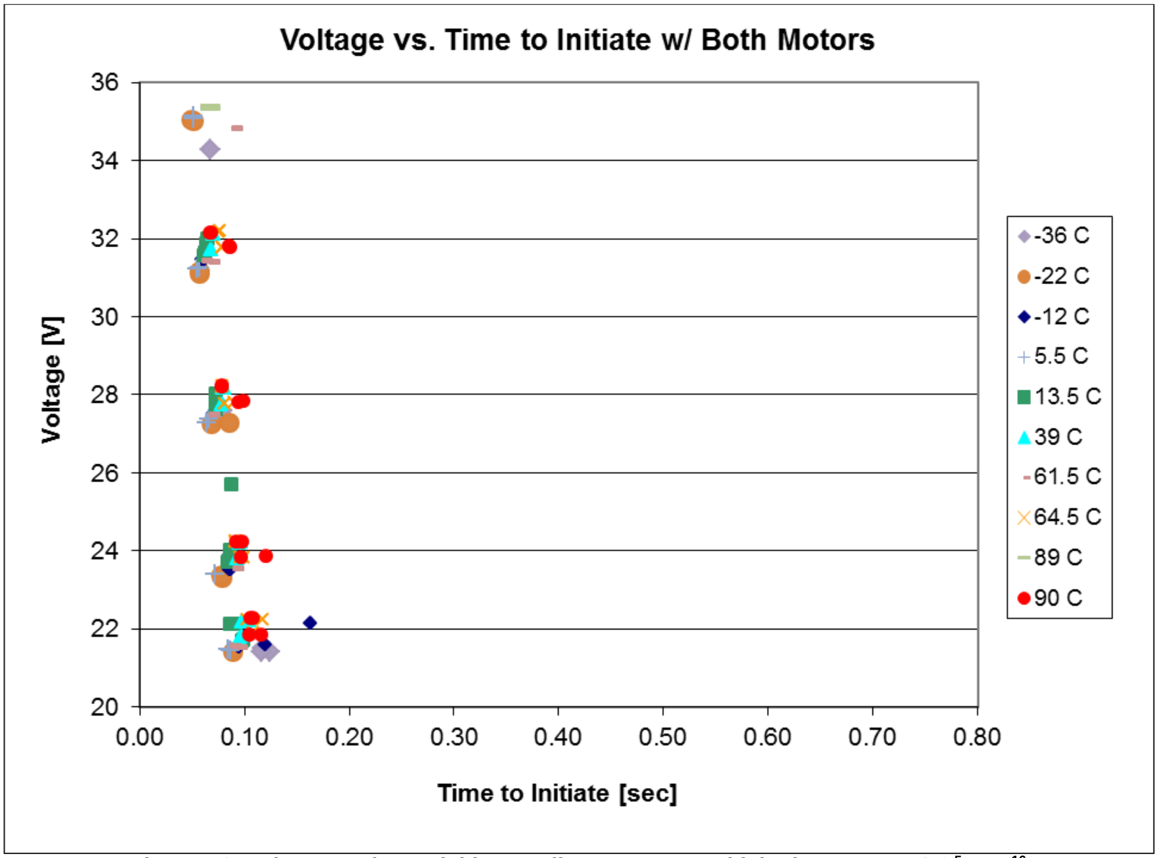


Figure 7-8: Voltage vs. time to initiate at all temperatures with both motors at ≤10^{-5} Torr[16]

[15] Source: PSC Documents 2002305-, 2001044-, and 2000715B.
[16] Source: PSC Documents 2002305-, 2001044-, and 2000715B.

7.8 Back EMF of the Motors

The Motors are connected to each other via bevel gears. Motors behave like direct current generators while running. If only one Motor is powered, the other will generate a voltage almost as high as the voltage of the powered motor, but with zero current.

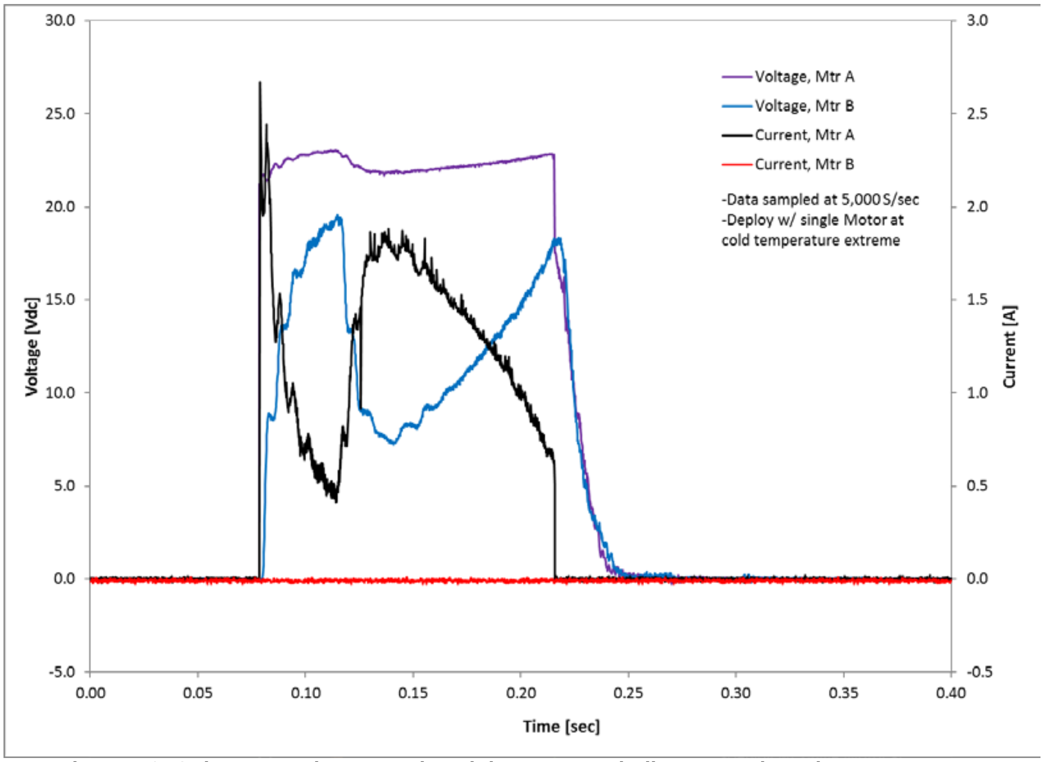


Figure 7-9: Only Motor A is powered, and thus Motor B indicates a voltage but not a current

7.9 Shorted Motors

When one of the Motors is shorted, the shorted Motor will act as a damper consuming most of the energy that the other Motor generates. The time-to-initiate will increase significantly. Do not short the motor(s)! Figure 7-10 shows the difference in time to initiate when a Motor is open versus shorted. An increase in time to initiate is clearly apparent at multiple temperatures.

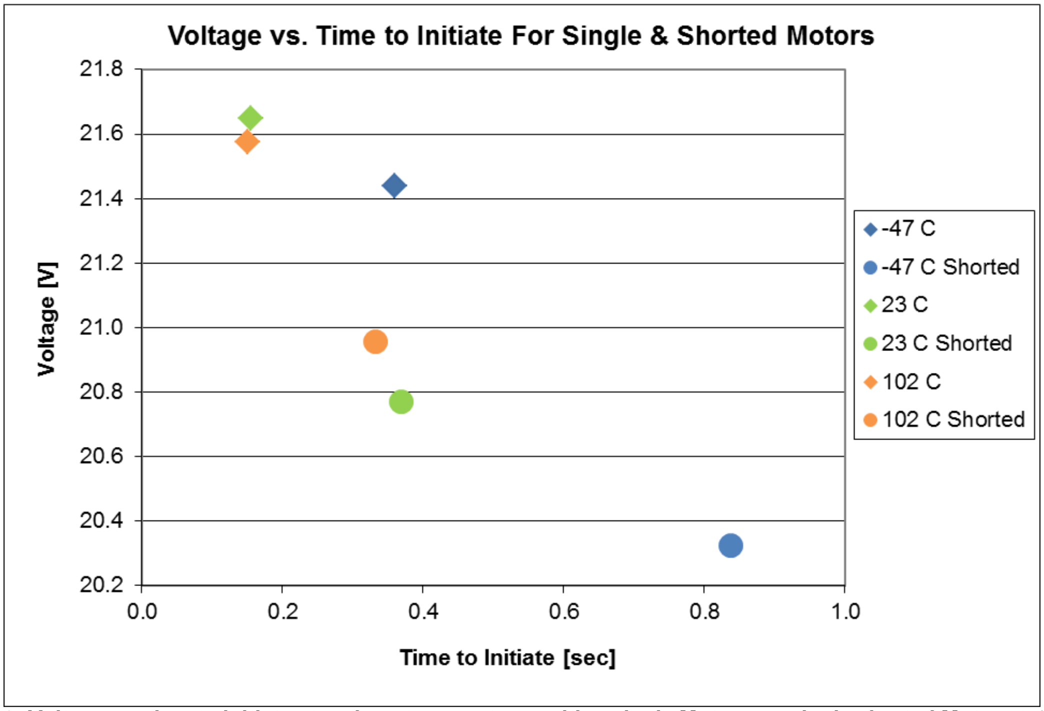


Figure 7-10: Voltage vs. time to initiate at various temperatures with a single Motor or a single shorted Motor at ≤10^{-5} Torr[17]

[17] Source: PSC Document 2002305-

7.10 Electrical Resistance

The resistance from the upper surface of the Upper Ring to the lower surface of the Lower Ring of the Lightband is 0.0070 ± 0.002 Ω. At least one Separation Connector is required to assure conductivity because the Upper Ring is anodized. The conductive path is through the Separation Connector shells and EMI gaskets in the Separation Connector Assemblies. Grounding to adjoining structures is achieved by using conductive fasteners from the Lightband to adjoining structures. The conductive shell of the DB-9 connector is fastened mechanically and electrically to the lower assembly of the Lightband.

7.11 Surface Charging

Because the Upper Ring has an anodized surface, it may be susceptible to localized surface charging. It is grounded to adjoining structures at each attachment bolt location (about every two inches along its circumference). The shells of the Separation Connectors are grounded at their mechanical interface to the Upper Ring via a local spot face where the anodized surface is removed. The Lower Ring is not anodized and its surface is fully conductive.

7.12 Radiation Sensitivity

The Lightband is not sensitive to radiation. The Lightband does not possess any integrated circuits or semi-conductors. There are no diodes, capacitors or resistors.

7.13 Static Sensitivity

The Lightband has no static-sensitive parts.

8. Thermal Properties

8.1 Value of Motors in Extreme Thermal Environments

The Lightband motors are DC brush motors. The brushes are made of a precious metal and not graphite (graphite should not be used in a vacuum because its performance degrades rapidly without water vapor). Extensive thermal-vacuum testing of these motors in Lightbands shows the motors are not susceptible to failure when used in the Lightband as a separation system.

The most extreme thermal environment for a Lightband was STS-116 (Dec. 9th through 22nd, 2006). Three Lightbands were used on the CAPE-ICU-I mission. ICU separated from the Shuttle on the 13th day of the mission. By then the 3 Lightbands had been exposed to approximately 250 (-25 to +70°C) thermal cycles. The temperature at separation was estimated to be -40°C. On STS-127 (July 2009), CAPE-ICU-II performed the same mission with 3 additional Lightband separations.

Figure 8-1: Three Lightbands used on STS-116 after approximately 200 (-25 to +60°C) thermal cycles

Generally, the thermal environment of unmanned missions is more benign than shuttle missions because the separation event on unmanned missions usually occurs within minutes of reaching orbit and because high-value spacecraft and the final stages of their launch vehicles go to substantial lengths to avoid temperature extremes.

All flight Lightbands are tested in a thermal-vacuum environment at PSC. The standard thermal vacuum test is shown in Section 18.1.2.

8.2 Survival and Operating limits

	Minimum [°C]	Maximum [°C]
Survival Limit	-68	+145
Operating Limit	-54	+128
Ideal Operating Temperature	+35	

Table 8-1: Survival and operating temperature limits[18]

Extensive testing has shown the ideal operating temperature is +35°C. This temperature minimizes time and energy required to initiate. At lower temperatures the energy and time to initiate increase because of the greater viscosity of lubricants and CTE mismatches of the components. As such, cold temperatures result in an increase preload of dynamic mechanized junctions. However, the Motors' winding resistance decreases at lower temperatures allowing more current to flow to the Motors and thus more torque to drive the initiation.

8.3 Absorptivity and Emissivity

The materials in Table 6-8 show the surface treatments of the Lightband components. They may not be modified by the addition of paint or tape because there is no area to apply such treatments. Specific measurements of thermal optical absorptivity and emissivity of the Lightband have not been performed as they are highly dependent upon variations in surface finish. For the clear hard anodize of the Lightband Upper Ring, PSC defers to industry accepted range for these values given in multiple sources[19]:

Lightband Characteristic	Range
Solar Absorptivity (α)	0.27 to 0.35
Emissivity (ε)	0.76 to 0.84

Table 8-2: Lightband absorptivity and emissivity ranges

Customers have occasionally inquired about the possibility of black anodizing components of the Lightband for the purpose of thermal balancing. The only components that can be black anodized are the Upper and Lower Rings. Typically though, black anodizing these parts is not worth doing because masked areas make up a substantial fraction of the total exposed area. Additionally, subsystems such as Separation Switches and Connectors obscure view factors of the remaining area. It should also be noted that black anodizing any component constitutes a custom Lightband and may incur additional cost and schedule duration.

8.4 Thermal Resistance

The thermal resistances of the Lightband vary by diameter as shown in Table 5-1. A full derivation is given in PSC Document *2000562 Thermal Resistance Test.*

[18] Source: PSC Document 2002305-

[19] Source: Appendix A of Spacecraft Thermal Control Handbook Volume 1, Edited by Gilmore

8.5 Nominal Thermal Response

The Lightband is intimately connected to massive adjoining structures on orbit. Typically its view factor to Earth, space, or the Sun is low due to the density and size of adjoining structures. As such, the Lightband temperature is primarily driven by conduction to and from adjoining vehicles. Adjoining space vehicles usually cannot tolerate temperatures outside of a 0 to +56°C band because these temperatures often exceed operating limits of propellants, electronics, and batteries which operate inside these vehicles.

8.6 Thermal Gradients and Transients

The Lightband has been separated while exposed to a substantial temperature differential between the Upper and Lower Rings. Section 4.2 of PSC Document *2000715* details the results of a test where 900 W was applied to the Lower Ring (emulating heating from a rocket motor) for 188 seconds preceding a separation at 10^{-5} Torr. Upon subsequent successful separation, the temperature difference between the Upper and Lower Ring of the Lightband was 30°C.

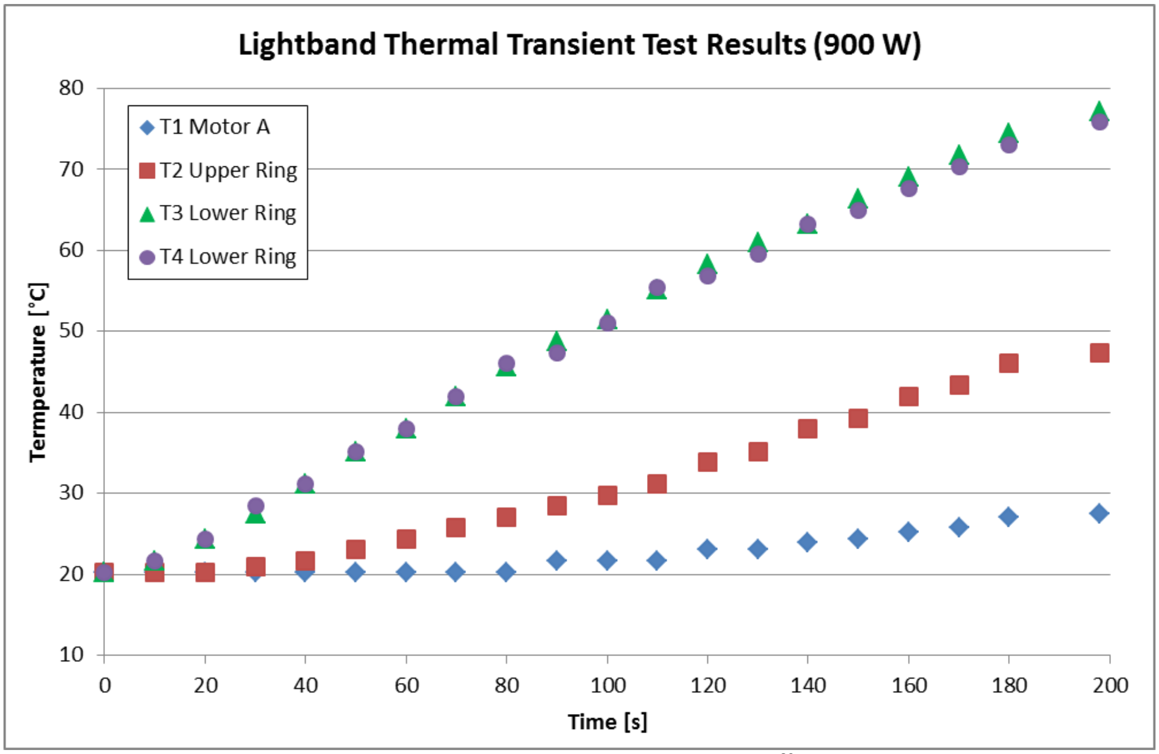


Figure 8-2: Thermal transient test results[20]

[20] Source: PSC Document 2000715A

9. Shock Properties

The Lightband generates shock during the separation event. Many PSC shock tests were excerpted to generate the following data on the shock of separation events and transmissibility. The shock response spectra (SRS) are calculated with 1/3 octave band frequency and 5% damping. Shock testing has consistently produced the determination that the Lightband substantially attenuates shock in a typical flight stack

9.1 Maximum Shock Generated by Lightband

To characterize shock produced by the Lightband, accelerometers are fastened to flanges of structures adjoining the Upper and Lower Rings. The accelerometers measure the expected shock at the simulated space and launch vehicle interfaces. Generally, shock at the Upper Ring Interface is less than at the Lower Ring interface. Since most customers focus more on minimizing shock at the Upper Ring interface because it is attached to a sensitive payload, the figures below show Upper Ring interface shock data.

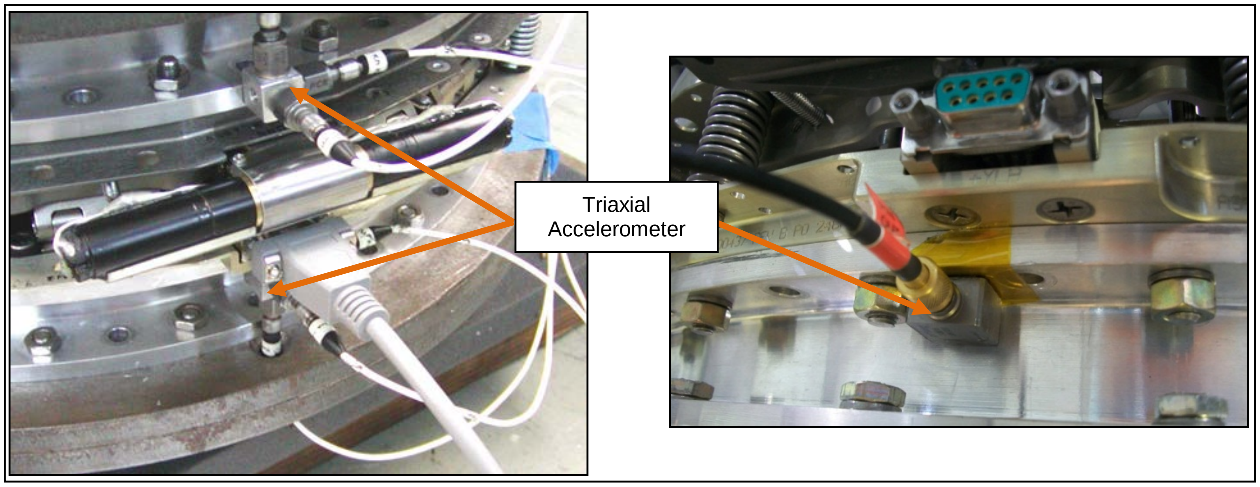


Figure 9-1: Examples of tri-axial accelerometers bonded to Transition Rings, fastened to the Lightband.

MLB Diameter [in]	Max. Upper Ring Interface Generated Shock, 100 Hz [g]	Max. Upper Ring Interface Generated Shock, 1,000 Hz [g]	Max. Upper Ring Interface Generated Shock, 10,000 Hz [g]
8.000	19	381	381
11.732	25	505	505
13.000	27	546	546
15.000	31	617	617
18.250	34	680	680
19.848	35	709	709
23.250	38	768	768
24.000	39	780	780
31.600	46	937	937
38.810	51	1038	1038

Table 9-1 Maximum Lightband-generated shock response spectrum at the Upper Ring interface[21]

[21] Source: PSC Document 2002258- & NASA-HDBK-7005 Section 5.3.4.1

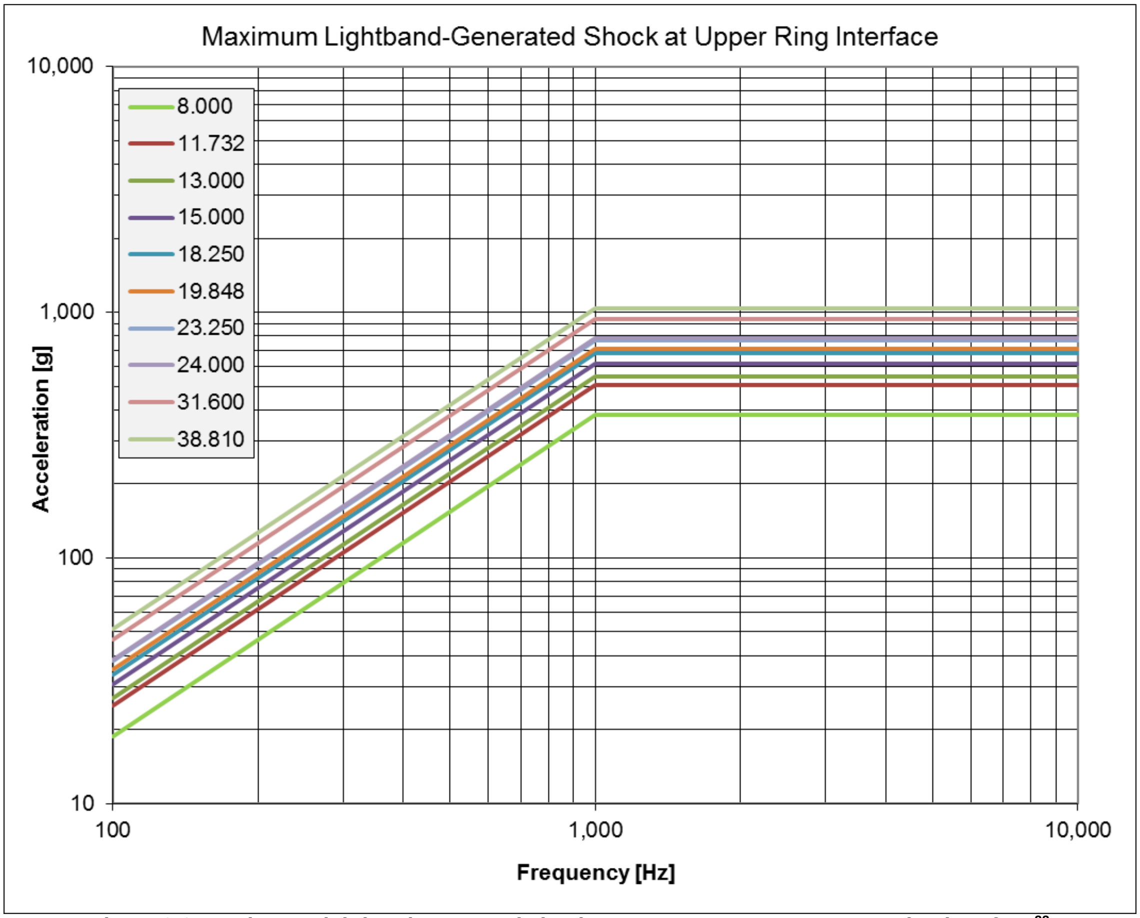


Figure 9-2: Maximum Lightband-generated shock response spectrum at Upper Ring interface[22]

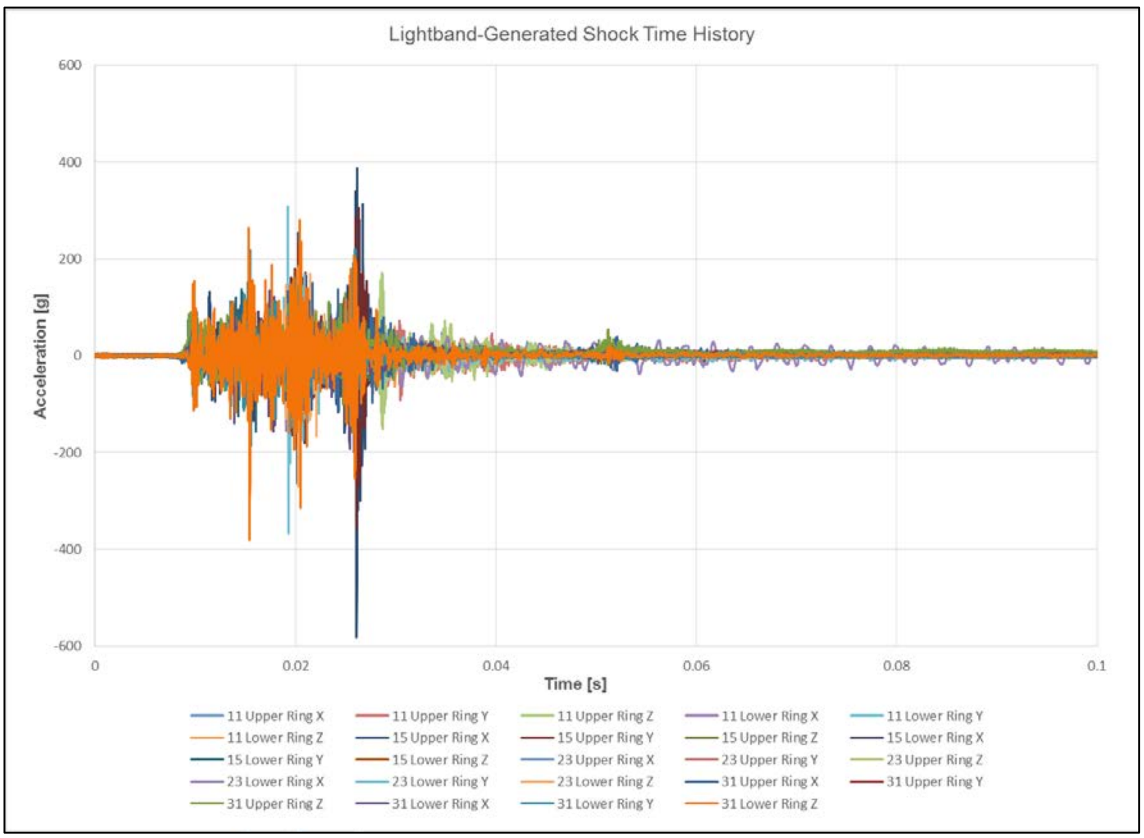


Figure 9-3: Nominal shock response time history from the Lightband separation (adjoining mass varies)[23]

[22] Source: PSC Document 2002258- & NASA-HDBK-7005 Section 5.3.4.1
[23] Source: PSC Document 2002258-

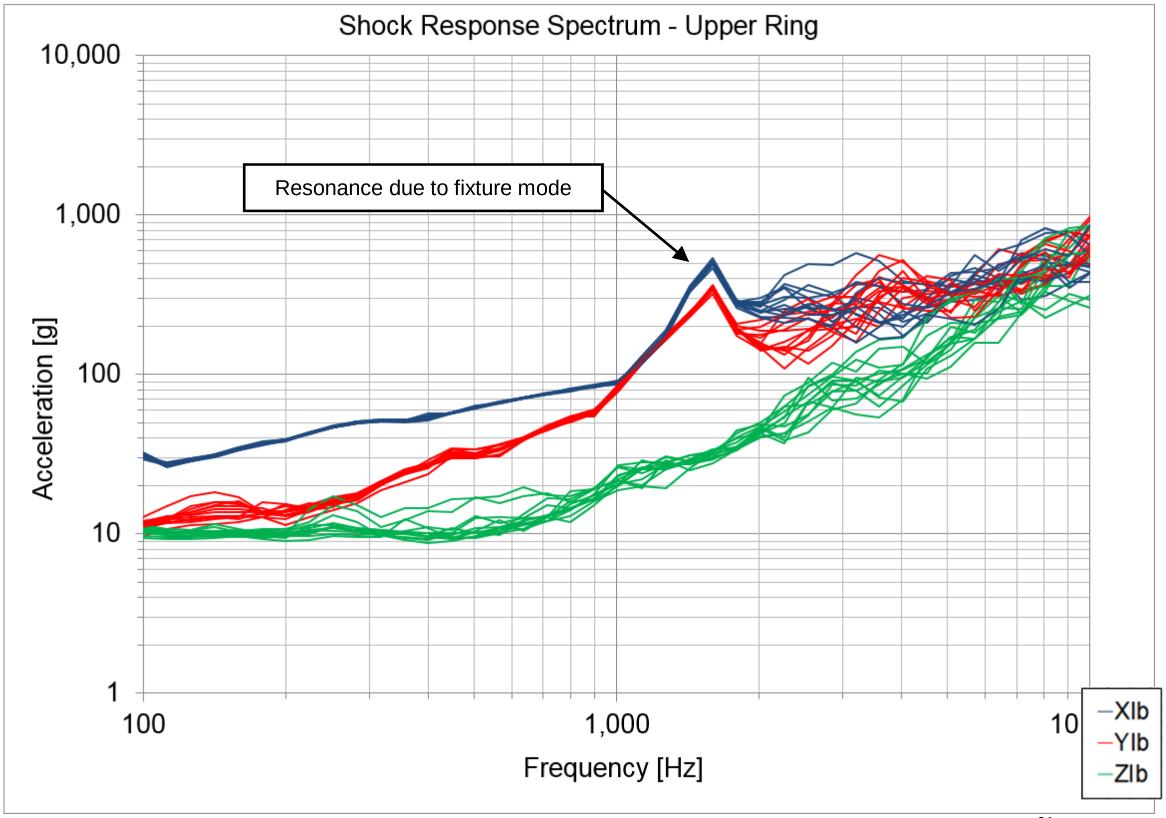


Figure 9-4: Nominal shock response spectrum at the Upper Ring interface for an MLB31.600[24]

Note that in Figure 9-4 a fixture mode is present at around 1,700 Hz. This mode explains the 5X amplitude resonance.

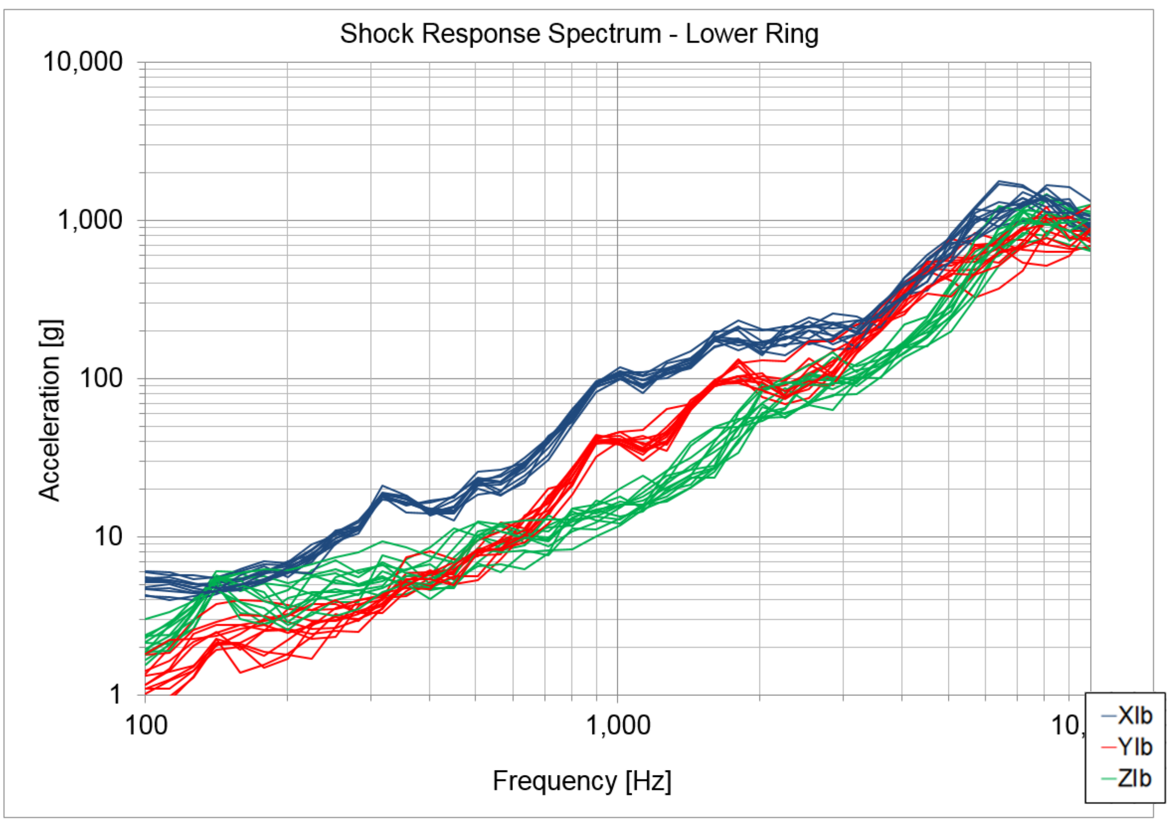


Figure 9-5: Nominal shock response spectrum at the Lower Ring interface for an MLB31.600[25]

[24] Source: PSC Document 2002317-
[25] Source: PSC Document 2002317-

9.2 Maximum Shock Applied to Lightband

Figure 9-6 and Table 9-2 show maximum shock applied to the Lightband in previous tests.[26] The Lightband was exposed to this shock input 3 times in each of the 3 Lightband axes. Data was acquired at least 100,000 samples per second. The shock response spectrum was computed with 1/6 octave band frequency intervals and 5% damping from 100 to 10,000 Hz. No detrimental yield or damage was found on the Lightband upon the completion of these shock trials and the Lightband did not auto-actuate.

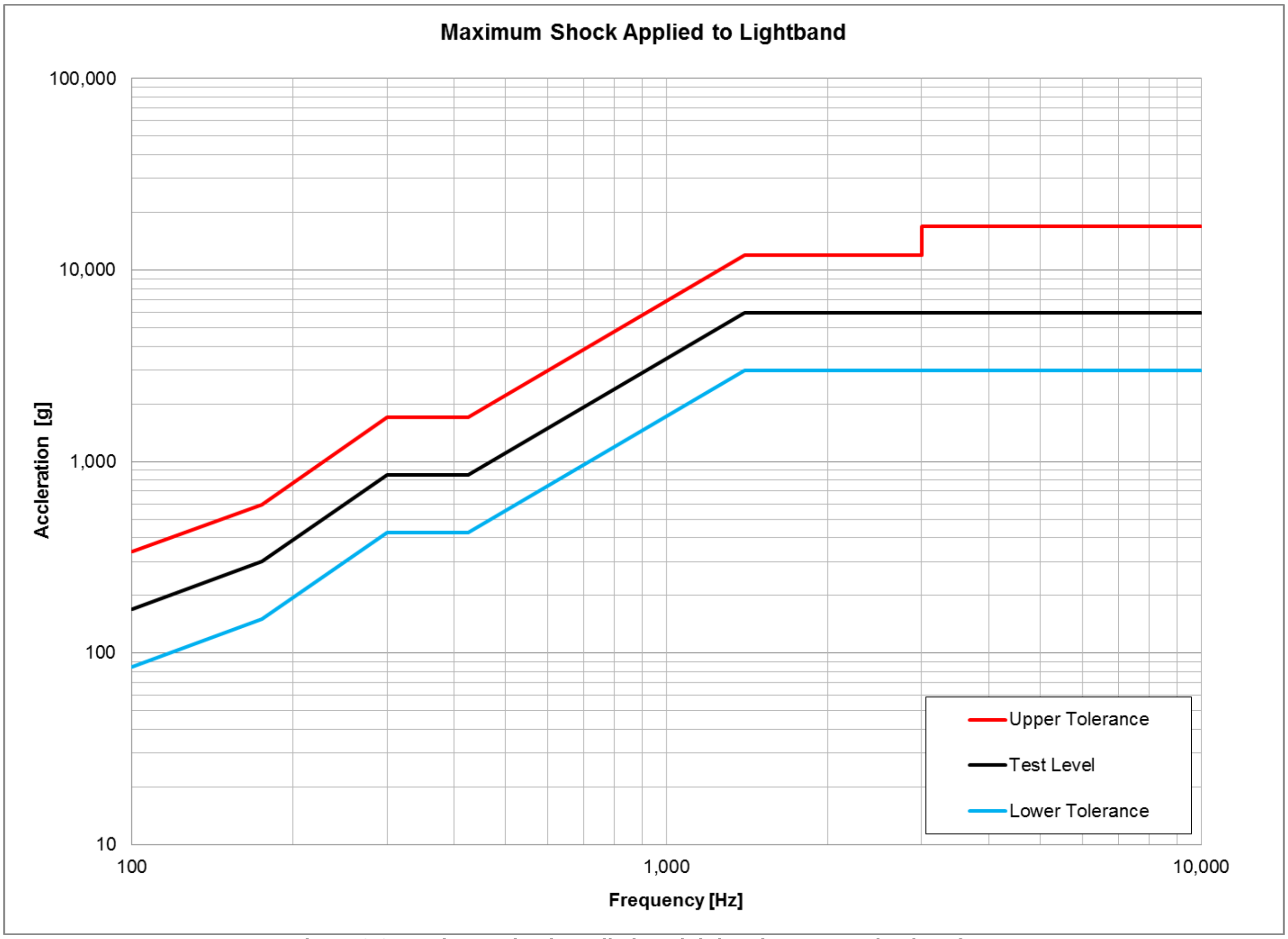


Figure 9-6: Maximum shock applied to Lightband at Lower Ring interface

Freq. [Hz]	Applied Acceleration [g]		
	Lower Tolerance	Nominal	Upper Tolerance
100	85	170	338
175	150	299	597
300	425	848	1,692
425	425	848	1,692
1,400	3,000	5,986	11,943
3,000	3,000	5,986	11,943
3,001	3,000	5,986	16,870
10,000	3,000	5,986	16,870

Table 9-2: Maximum shock applied to Lightband

[26] Source: PSC Document 2002081F.

10. Reliability

Probability of Success	Confidence Level [%]
>0.999	60
>0.999	85
>0.998	95
>0.998	97.5

Table 10-1: Minimum reliability and corresponding confidence level

Table 10-1 was calculated using Table 22.4 of *Space Vehicle Mechanisms* by Peter L. Conley given approximately 1,000 no failure tests. Lightbands have cumulatively been operated more than 2,300 times during testing and flight operations[27]. Therefore the probability of successful Lightband separation is greater than 99.8% with a confidence interval of 95%.

As of the revision date of this document, the Lightband has operated successfully more than 45 times in spaceflight. There have been no failures to operate in spaceflight.

Prior to spaceflight, each Lightband is separated approximately 12-17 times to verify operability. These operations are part of acceptance test programs conducted by PSC. As shown in Table 10-2, the Lightband allows the user to verify operation multiple times before in-flight separation.

	Fairing Sep System	Pyrotechnic Sep System	Motorized Lightband
Typical quantity of separations on flight unit	0	0	12-17

Table 10-2: Comparison of separation system separations before launch

Alternatively, PSC tests development and qualification units to examine reliability limits and inform the allowable limits of Lightbands in ground test and space flight. A typical qualification test will result in more than 100 separation tests on a single Lightband. These separation tests are part of all environmental tests.

Because of the reusability of the Lightband and the high production rate, it has been inexpensive to amass test data that is several orders of magnitude larger than competing pyrotechnic systems. The Lightband was designed to be reusable with the intent of demonstrating reliability.

Stowing consumes about 10 times more energy than deploying. So the act of stowing the Lightband before flight accurately indicates the capacity of the Lightband to deploy and separate on orbit. If the Lightband cannot be stowed, it indicates one of the motors is inoperable. The setting-for-flight operation (completed after the Lightband is stowed) is a low power operation completed by both motors. If the current into the motors is monitored during this operation as prescribed in PSC Document *2000781 MLB Operating Procedure*, it will provide data to clearly indicate the capacity of the Lightband to operate properly on orbit.

Maximum reliability of the Lightband can be attained by minimizing the power conducted into the Lightband and the number of cycles. Specifically, avoid unnecessary stow/deploy operations and minimize applied voltage levels as higher voltages will put more power into the mechanism. More power increases stresses to the Motor Bracket Assembly.

PSC constantly advances the Lightband technology to increase reliability during ground test and in flight. By building and testing about 20-30 flight Lightbands per year, PSC engineers are made aware of trends that may compromise reliability.

[27] Source: PSC Document 2002675C.

11. Failure Modes and Effects Analysis (FMEA)

PSC Document *2000770A MkII Motorized Lightband Failure Modes and Effects Analysis* provides a detailed Lightband FMEA. The FMEA has four major sections: Primary Load Path, Motor Bracket Assembly, Subsystems, and Human Error.

The most common source of Lightband failure has been customer user error because they neglected to read the operating procedure and receive training. Here are a few examples:

- A customer disregarded the operating procedure, bypassed the Limit Switches, turned off the power supply's current limit, and then used a screw driver to help the Lightband stow. It was already stowed, which led to irreparable damage.

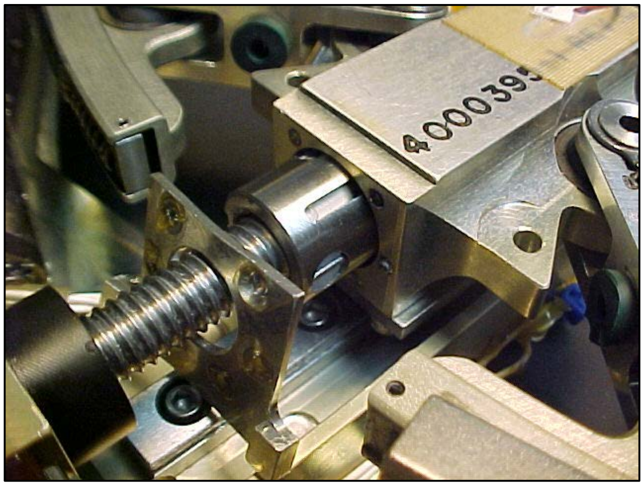


Figure 11-1: End plate ripped off Sliding Tube because the Lightband was not properly operated

- A customer forgot to force limit vibration inputs while performing a random vibration test and cracked a Lightband Leaf then continued the test without noticing the cracked Leaf

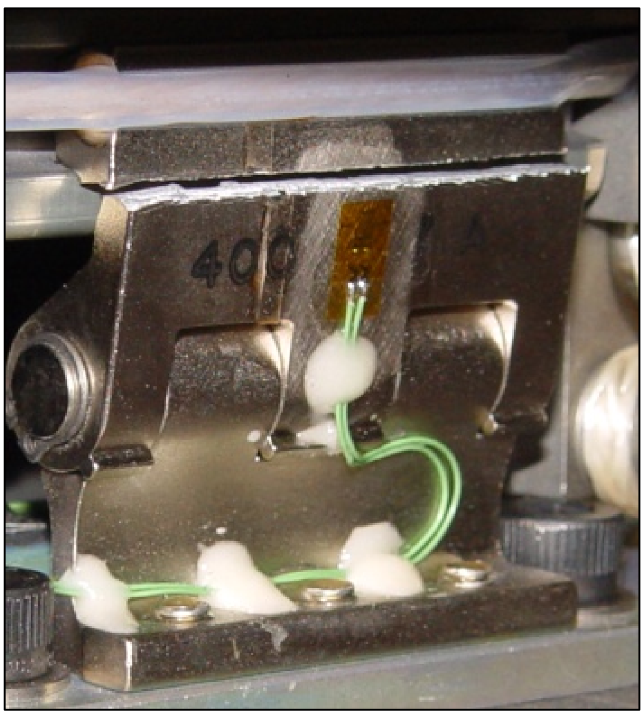


Figure 11-2: A Leaf from a Lightband cracked in half during a flawed random vibration test

- A customer had PSC engineers fly to Kodiak, Alaska to fix what was thought to be a broken Lightband only to discover the customer was improperly operating a multimeter used to verify Lightband operation.
- A customer forgot the Lightband was connected to the power supply during a ground test of the initiation electronics. The Lightband deployed and the separated cantilevered structure damaged the Lightband.
- A customer miswired the cable from the launch vehicle to the Lightband resulting in stalled Motors for approximately 60 seconds.

The most common customer errors arise when they fail to follow procedures properly or fail to verify electrical connections. These failures typically occur soon after receipt by customer and at considerable cost. To prevent this failure mode, all Lightband users are required to complete the aforementioned Lightband training course provided by PSC at no extra cost and urged to study this manual in detail. See Section 23.

12. Cleanliness & Handling

12.1 Customer Cleanliness and Handling Requirements

Users shall store and operate the Lightband in a visibly clean environment. The Lightband shall be covered when not in use. The Lightband may be handled without gloves, as long as handling precautions outlined in *2000781 MLB Operating Procedure* are followed.

12.2 Cleanliness and Handling at PSC

The Lightband is assembled and tested in a visibly clean environment. The thermal vacuum acceptance test that every Lightband undergoes tends to boil-off volatile contaminants. As such, the thermal-vacuum test tends to clean the Lightband of volatile materials or expose the presence of unacceptable contamination. The Lightbands are covered when not in use at PSC. Section 24 outlines the contamination control methods used in shipping.

12.3 Cleanliness Precautions

The Viton bumpers can shed (<0.005 square inch) debris if the Lightband is stowed and deployed beyond its useable life. See Figure 6-12 for an image of the Viton Bumpers and Section 6.15 for discussion of Lightband usable life.

When the Lightband is separated and not attached to other structures, it is in its most flexible and fragile state. When the Motor Assembly is exposed to accidental loading the mechanical junctions may loosen. In extreme cases, this could lead to cracking of Motor Assembly components or debris creation.

The Separation Connectors can collect debris when the Lightband is in a deployed state. This can lead to inadvertent intermittencies. PSC recommends that the exposed Separation Connector pins be covered when in the deployed state for extended durations.

Lubricant (Braycote 601 and molybdenum disulfide mixture) is applied in several locations and should not be removed by cleaning processes. Lubricant is located in the Motor Bracket Assembly, the Retaining Ring Assembly, the Leaf Assemblies, and in the accepting groove of the Upper Ring. See *2000781 MLB Operating Procedure for additional details.*

13. Storage Requirements

Store the Lightband in a sealed enclosure in relative humidity of less than 95% at temperatures between 0 and 50°C. If possible, store the Lightband in the deployed state to minimize strain on components. The maximum allowable storage durations are shown in Table 13-1.

Lightband State	Max. Allowable Storage Duration [years]	Before Operating Lightband beyond this Storage Duration
Stowed	1	Contact PSC for approval
Set-For-Flight	1	Contact PSC for approval
Deployed	3	Contact PSC for approval

Table 13-1: Lightband storage limitations

The Separation Springs do not creep due to long term storage and the Lightband can remain stowed and ready for separation. The shelf life of a Lightband is estimated to be 20 years, but PSC shall be contacted for approval before operation if any of the allowable storage durations given in Table 13-1 are exceeded.

The most extreme storage environment a Lightband has been exposed to was the STS-116 and STS-127 missions. In those cases, six Lightbands were on-orbit stowed in Shuttle's bay for more than two weeks after sitting on the launch pad for several months. The uncontrolled thermal cycling, about 250 cycles from -25 to +70°C at 10^{-9} Torr, is an extremely rigorous verification of the Lightband's capacity to operate after long-term storage.

In another example, a Lightband on the STP-S26 mission remained stowed on-orbit for more than 90 days because of a satellite communication issue. Upon receiving the separation signal from the final stage 3 months later than planned, the Lightband separated nominally.

14. Lightband Operation & Integration

CAUTION: Operating the Lightband before receiving training from PSC will void the Lightband's warranty. See Section 23.

All Lightband users are required to complete a training course conducted by PSC engineers. It is the customer's responsibility to ensure that they have been trained before operating the Lightband. This training is included in the cost of the Lightband and generally performed at PSC's facility in Silver Spring, Maryland. Remote training is available at potentially additional cost. Without this training the probability of user-induced failure will be high. See Section 23.

The latest revision of PSC Document 2000781 MkII MLB Operating Procedure details the steps to stow, set-for-flight, and deploy the Lightband.

14.1 Access to Fasteners

When the Lightband is separated, the fasteners to the adjoining structures are readily accessible. When the Lightband is stowed, access to fasteners is limited but possible if there is access form the inside (such as in ESPA). Hex drivers (Allen keys) need to be shortened. Access from the inside is very valuable when removing a stowed Lightband from an adjoining structure.

14.2 Vertical and Horizontal Integration to Adjoining Vehicles

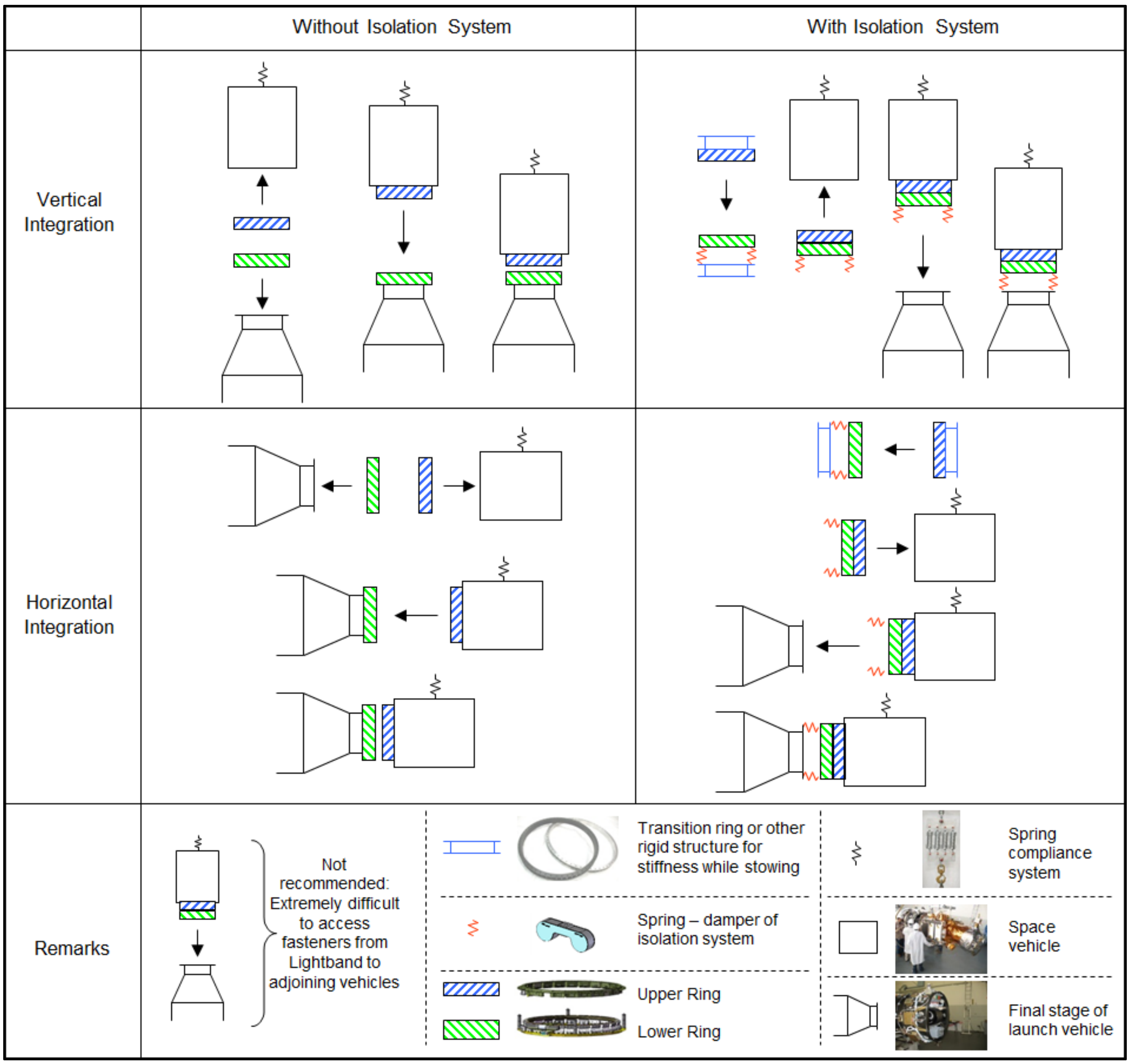


Figure 14-1: Typical vertical and horizontal integration methods

Vertical integration allows the weight of the space vehicle to compress the Separation Springs. Horizontal integration requires the capacity to compress the Separation Springs (such as a clamp that straddled the space vehicle). PSC manufactures proprietary Lightband Compression Tools that can be used for this purpose as well. See Section 22.

Isolation systems simplify integration because they remove the need to stow the Lightband in the field, alleviate flatness requirements, and add compliance to the system. Transition Rings can be used to simplify integration. See Section 22.

The compliance of the entire stack needs to be assessed in order to properly integrate the Lightband. When the Lightband is stowed as part of the integration process, the whole system will be structurally indeterminate. If the space vehicle and Upper Ring are too far from the Lower Ring or improperly aligned, the Lightband will have to pull the space vehicle down and vice versa. To minimize this effect, a compliance spring and/or a more precise control of space vehicle position in all six degrees of freedom is necessary.

Flatness of the adjoining surfaces should be within the flatness requirement defined in Table 5-1. If flatness requirements are not met by the structure, shims (epoxy or metal) can be used to attain the required flatness.

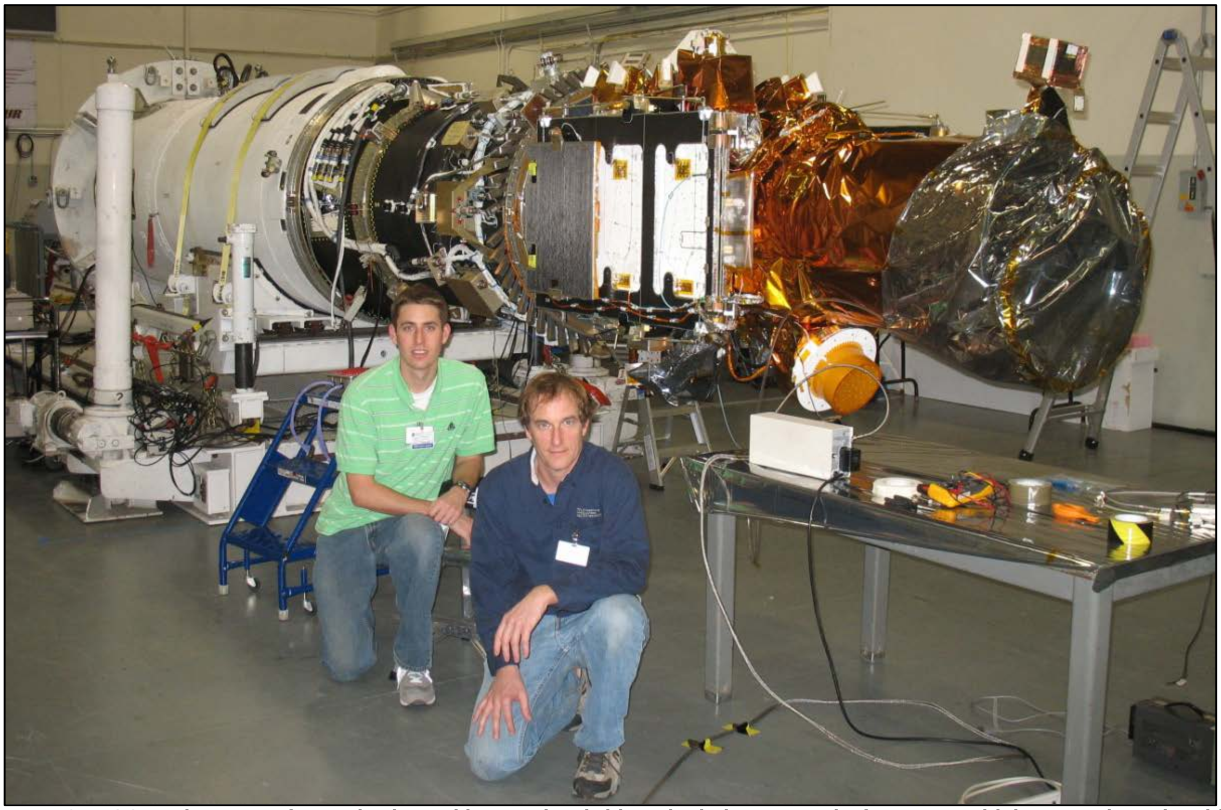


Figure 14-2: PSC engineers perform a horizontal integration (with an isolation system) of a space vehicle onto a launch vehicle

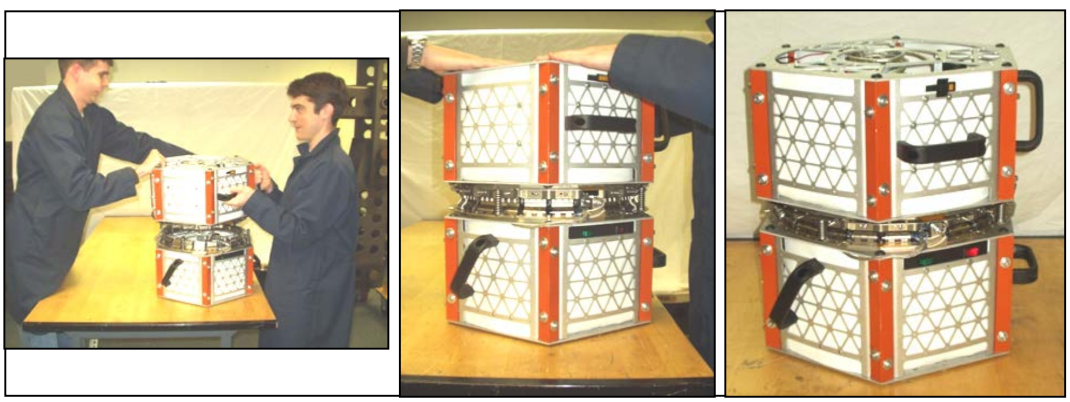


Figure 14-3: PSC customers perform a vertical integration (NanoSat)

Figure 14-4: PSC engineers perform a vertical integration (CAPE-ICU-I)

15. Selecting a Lightband

There are many determinations that must be made when a customer is selecting a Lightband to purchase. This section outlines the process and choices.

Any Lightband that deviates from requirements defined in this document (e.g. requires custom features, additional testing, different procedures, or different compliance documents) it is considered a Custom Lightband. Prospective users should be aware that the cost and schedule of Custom Lightbands is often substantially greater than the Standard Lightband presented in this document. See Figure 15-2.

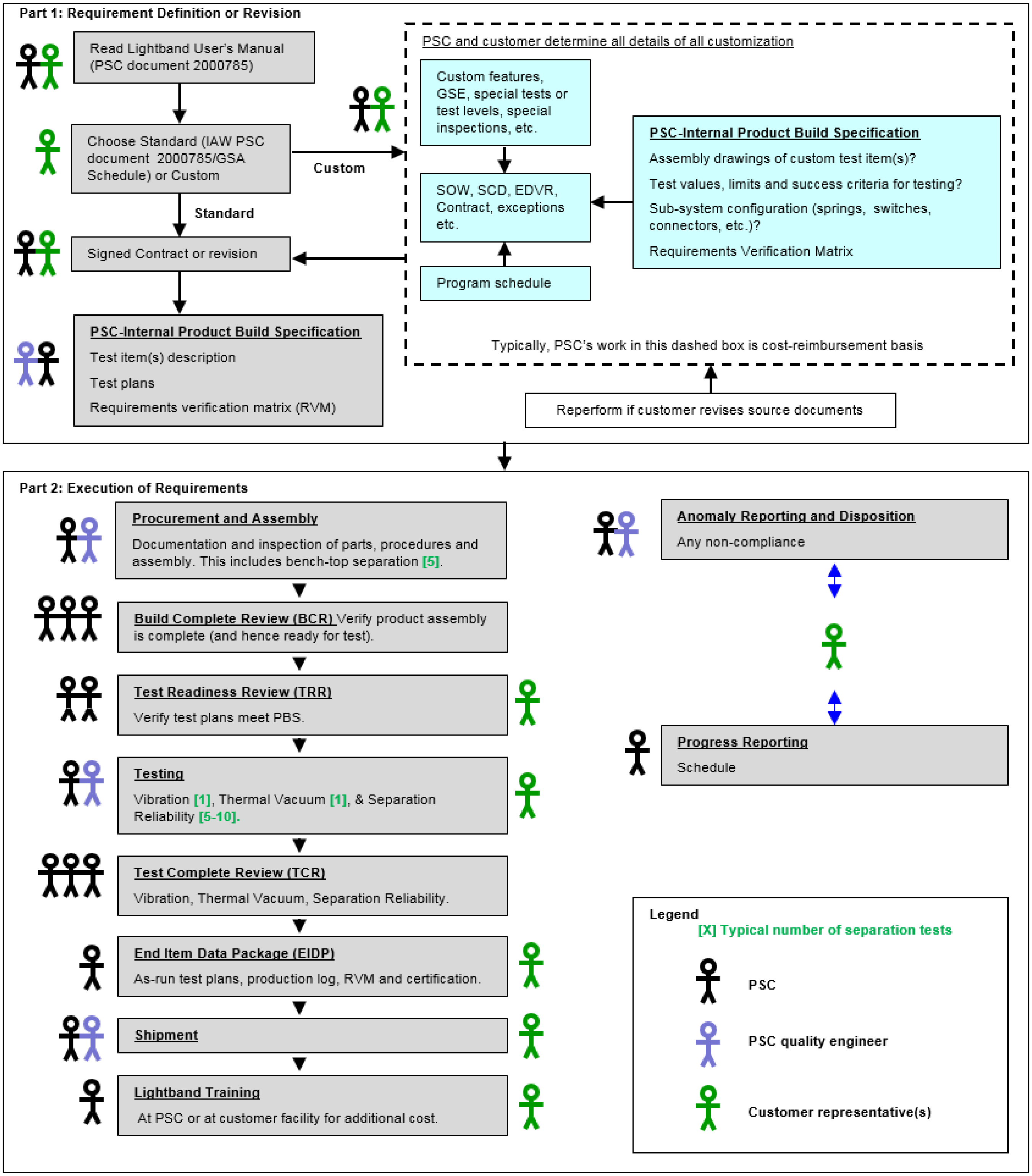


Figure 15-1: Lightband selection and production process

Standard Lightband	Custom Lightband
• No deviation from current Lightband design • Only 3 reqs. supplied by customer: sep. velocity, payload mass & final stage mass. • Random vibration test • Thermal vacuum test • Separation reliability test	• Any tests not in standard regimen • Any deviation from standard test requirements • Any requierment or contractual obligation not in this User Manual. • Additional cost • Additional schedule duration

Figure 15-2: Standard vs. Custom Lightband characteristics

Custom Lightband Inquiry Item	Document Reference Section	Response [Y/N]
Is strength testing required?	18.2.1	
Is shock testing required?	18.2.2	
Is any non-standard test required?	18.1	
Are Roll Brackets required?	15.1.10	
Are Lightband Compression Tools required?	15.1.11	
Is a custom design modification feature required?	6.1	
Are non-standard rotation rates required?	18.1.3	
Is a separation velocity tolerance tighter standard ±25% value?	18.1.3	
Are requirements outside of this User Manual being referenced in a statement of work or separate compliance document?	15	
If any of the above are answered as “yes,” the Lightband shall be classified as Custom.		

Table 15-1: Standard vs. Custom Lightband selection checklist
(Note: checklist is not all-encompassing, there may be additional unlisted items which necessitate Custom classification)

15.1 Lightband Selection Steps

The following steps shall be completed by the customer to determine the correct Lightband size for their mission requirements.

15.1.1 Read this manual

If you thoroughly understand the Lightband, you will be in the best position to avoid costly test failures and program delays.

15.1.2 Determine stiffness requirements

The biggest driver in Lightband diameter selection should be payload stiffness requirements. From dynamic envelope mission requirements, determine the required axial and lateral stiffness of the payload stack. The minimum Lightband diameter can then be selected from Table 5-1. However, it is prudent to choose a Lightband diameter larger than necessary to provide additional stiffness margin at less than an equivalent increase in weight. For example, a 15 inch diameter Lightband is about 6.6 times stiffer than an 8 inch diameter Lightband, but weighs only twice as much. See Section 6.6.

15.1.3 Determine strength requirements

From your expected mission loads on the payload, calculate maximum line load via methods in Section 6.10. Verify that mission loads required to attain those line loads are less than maximum Lightband loads shown in Table 5-1. It is not sufficient to only be below maximum line loading, it is also necessary to be below maximum loading.

15.1.4 Determine cyclic loading and fatigue requirements

Determine if the mission vibration environment will cause an exceedance of allowable line loading. If so, increase the chosen Lightband diameter until allowable line load is not exceeded.

15.1.5 Select a Lightband diameter

Choose an appropriate Lightband diameter from Table 5-1 based on stiffness, strength, cyclic loading, and fatigue requirements,

15.1.6 Determine payload and final stage masses

Payload and final stage masses are necessary to predict flight separation velocity based on tested separation velocity.

15.1.7 Determine separation velocity requirement

Determine the separation velocity that the Lightband must impart to the payload. If no separation velocity requirement exists, PSC defaults to a separation velocity requirement of 1.00±0.25 feet per second. Separation velocity is, of course, driven by payload and final stage masses. Any separation velocity that requires more or fewer Separation Springs than shown as allowable in Table 5-1 shall be considered a Custom Lightband. If a Custom Lightband is not desired, PSC will default to the closest Separating Spring quantity allowable in in Table 5-1. The standard separation velocity tolerance is ±25%. Section 6.21 details how to calculate the estimated spring quantity.

15.1.8 Determine Separation Switch quantity

The greater the quantity of Separation Switches, the more complex and heavy the harness. By default PSC can include two Separation Switches in the price of every Lightband. If more than two Separation Switches are required an additional cost is typically incurred.

15.1.9 Determine Separation Connector quantity

As with Separation Switches, fewer Separation Connectors allow for a simpler harness. At least one Separation Connector is required to ensure conductivity through the Lightband because the Upper Ring is anodized. By default PSC can include two Separation Connectors in the price of every Lightband. If more than two Separation Connectors are required an additional cost is typically incurred.

15.1.10 Determine Roll Bracket quantity (Lightband will be classified as Custom)

Sometimes customers require a rotation rate about the space vehicle's thrust axis following separation. Lightbands can produce roll rates up to approximately 10 degrees per second via installation of proprietary Roll Bracket Assemblies. During separation, the assemblies' rollers contact each other, inducing a roll rate about the X_{LB} axis. The Roll Bracket Assembly mounts on the same features as the Separation Connector and Switch and thus the sum of Connectors, Switches, and Roll Brackets must be less than or equal to the allowable quantity given in Table 5-1. Roll Brackets are not standard accessories and therefore their inclusion will classify a Lightband as custom. Customers should contact PSC if interested.

15.1.11 Determine Lightband Compression Tool quantity (Lightband will be classified as Custom)

If the mass of the payload is less than total Separation Spring force, a means to compress the Lightband before stowing is required. This typically occurs with payloads being horizontally integrated or when the payload mass is relatively small. PSC manufacturers Lightband Compression Tools (LCTs) for this purpose. LCTs are a separate product that must be purchased along with the Lightband and specified at time of purchase like Separation Connectors or Switches. The quantity required is approximately one pair per Separation Spring as each pair provides approximately 20 lbs. of compression force. In cases where a high quantity of Separation Springs are installed on a smaller diameter Lightband, it is sometimes not possible to install the recommended quantity of LCTs. See Section 6.21, Section 14.2, and Table 22-1 for more information.

15.1.12 Complete virtual fit check and plan logistics

Integrate a CAD model of the Lightband (download from planetarysystemscorp.com or contact PSC) with a model of your payload and verify your fit requirements. Remember to include your wiring harness. Also determine how you will fasten and operate the Lightband for shipment, testing and final integration procedures. Determine the electrical and mechanical ground support equipment (GSE) needed.

15.1.13 Determine test regimen

PSC performs three standard acceptance tests: random vibration, thermal vacuum, and separation reliability IAW Section 18.1 of this document. Optional testing includes strength and shock tests. If further testing is required, please contact PSC.

15.1.14 Select Flight or Engineering Development Unit

EDU Lightbands differ from flight Lightbands in that EDUs receive only a bench-top separation test rather than a full slate of acceptance testing prior to shipment. Customers often purchase an EDU in addition to a flight unit for fit checks and ground testing. Because they do not receive acceptance testing, EDUs shall not be used for flight. As such, EDUs are indelibly marked "***NOT FOR FLIGHT***."

15.1.15 Specify the Lightband

Use the convention MLBXX.XXX- SW-SC-R-T-FLT-DV-PM-FM to specify the Lightband you need:

Lightband	Bolt Circle Diameter	Separation Switch Qty.	Separation Connector Qty.	Roll Bracket Pair Qty.	Lightband Compression Tool Qty.	End Use (Flight or EDU)	Separation Velocity [ft/s]	Payload Mass [lb]	Final Stage Mass [lb]
MLB	XX.XXX	SW	SC	R	T	FLT	DV	PM	FM

Table 15-2: Lightband specification convention

For example, MLB15.000-2-1-0-8-FLT-1-396-3000 specifies a 15 inch bolt circle diameter Lightband with 2 Separation Switches, 1 Separation Connector, 0 Roll Brackets, 8 Lightband Compression Tool pairs that will receive standard acceptance testing, be used for a space flight, have flight separation velocity of 1.0 ft/s, and separate a payload of 396 lbs. from a final stage of 3,000 lbs. Using this convention will ensure that Lightband requirements are unambiguous.

15.1.16 Contact PSC

Contact PSC by email (info@planetarysystemscorp.com) or phone to finalize the selection and purchase of a Lightband.

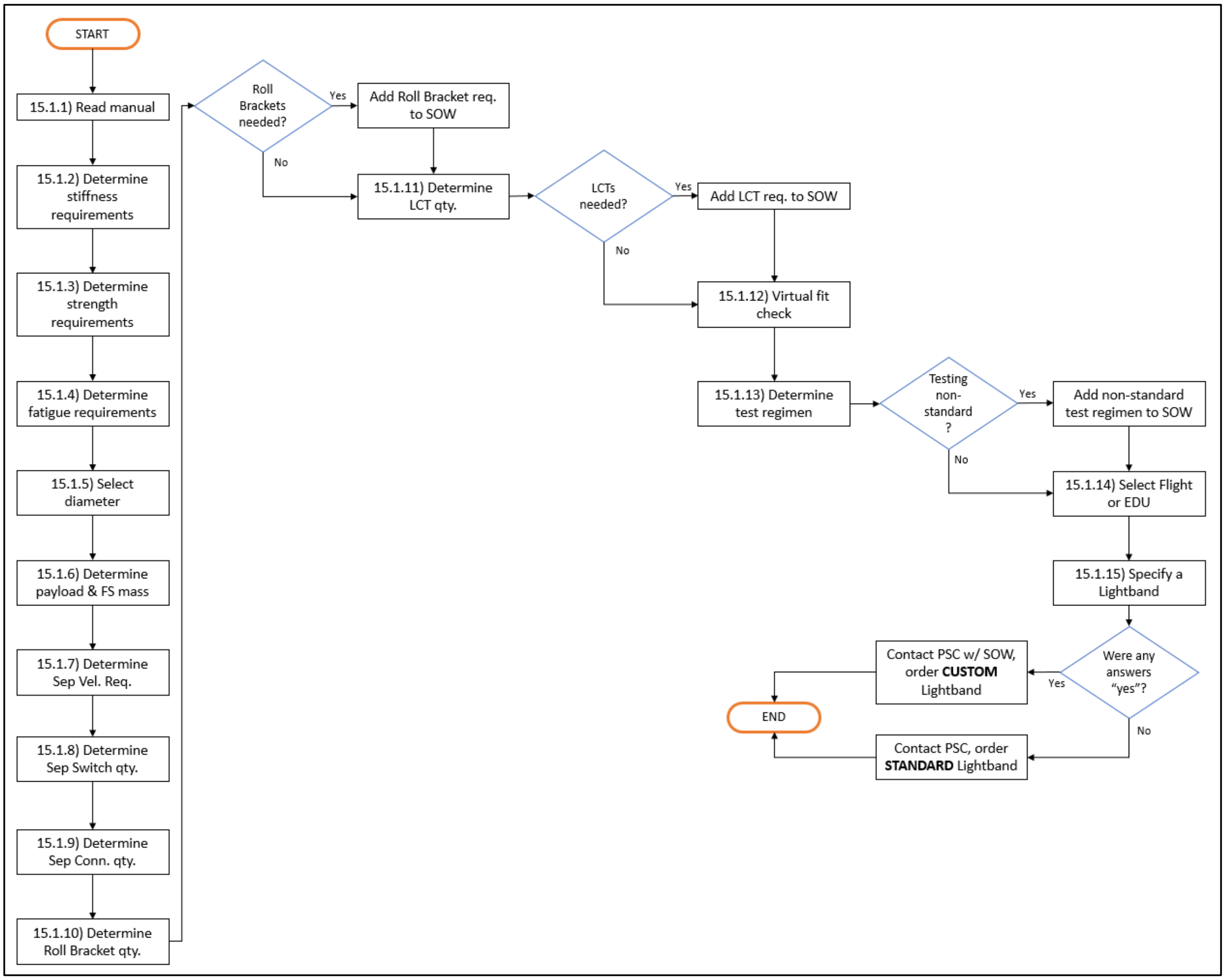


Figure 15-3: Lightband selection process flow chart

16. Purchasing, Deliverables, & Schedule

16.1 Purchasing a Lightband

Lightband prices are listed on the GSA Schedule. Contact PSC directly to receive the most up-to-date prices. The standard payment schedule is shown in Table 16-1.

Event	Payment [%]
Receipt of order	50
Build complete review (BCR) completion	25
Shipment	25

Table 16-1: Standard payment schedule

16.2 Standard Delivery Schedule

Standard Lightbands are typically delivered in 7 months ARO. Some Lightbands can be delivered as fast as 4 months after receiving order, however the price is higher.

Time, after receipt of order (ARO) [Months]	1	2	3	4	5	6	7
Part Fabrication	X	X	X				
Assembly				X	X		
Test Readiness Review (TRR)					X		
Acceptance Testing						X	X
Ship							X

Table 16-2: Standard Lightband schedule

16.3 Expedited 15 Inch Diameter Delivery Schedule

PSC often carries 15 inch diameter Lightbands in stock. If available, these can be delivered in 1 to 2 months or less at a potentially reduced cost. Contact PSC for more information and availability.

Time, after receipt of order (ARO) [Months]	1	2
Test Readiness Review (TRR)	X	
Acceptance Testing	X	X
Ship		X

Table 16-3: MLB15 typical expedited schedule

16.4 Custom Lightband Schedule

Whenever a Lightband deviates from requirements defined in this document (e.g. requires custom features, additional testing, different procedures, or different compliance documents) it is by definition a Custom Lightband. Prospective users should be aware that the cost and schedule of custom Lightbands is often substantially greater than the standard Lightband presented in this document. Table 16-4 outlines a typical custom Lightband program.

Event	Description	Deliverables from PSC	Preferred Contract Type
Phase I	Complete specification of the customization	• Assembly drawings • All test procedures • Custom tooling, design, and dwgs • Manufacturing and test schedule • Anomaly reporting	Cost plus fixed fee or time and materials
Phase II	Build and test Lightbands to Phase I	• Lightbands • Test results	Firm fixed price
Any change to Phase I	Any "to be determined" or any change in requirements that exceeds specifications in Phase I	Modifications for hardware, procedure, schedule, etc.	Cost plus fixed fee or time and materials

Table 16-4: Typical custom Lightband program

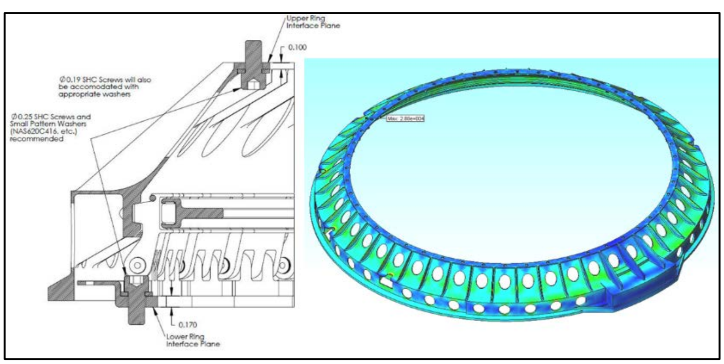


Figure 16-1: Custom work example - modified Upper Ring for an MLB31.600 Mk II used on the IBEX program

16.5 Lightband Deliverables

The items included in the price of a Lightband and delivered to the customer are:

1. The Lightband(s)
2. The production log which provides detailed traceability of parts, procedures and other materials. It is also a complete build log of the Lightband.
3. Copies of all as-run test procedures and reports
4. Certificate(s) of conformance
5. Training on Lightband operation (at PSC's facility)

Additional deliverables may be included in the case of custom Lightbands.

16.6 Lightband STEP Files

STEP files of Lightband assemblies are available to prospective users and customers for download. These include models of the Lightband deployed and stowed. These models allow the generation of unique Separation Spring, Connector and Switch configuration. PSC reserves the right to move Separation Spring locations to satisfy rotation rate requirements when PSC completes separation reliability testing on flight Lightbands.

16.7 Assembly Drawings

PDFs of assembly drawings can be made available to customers before delivery. Assembly drawings include bills of material. This item is subject to US Export Control regulation.

16.8 Lightband Finite Element Models

PSC has test-verified finite element models (FEM) of Lightbands available for customers. Contact PSC for further information. This item is subject to US Export Control regulation.

17. Manufacturing Process

Engineers at PSC design, assemble, and test Lightbands. PSC is an AS 9100-compliant organization. All of the machining and fabrication is completed by vendors qualified to PSC's standards. PSC maintains documentation of all tasks associated with flight hardware procurement, storage, assembly, test, and shipment. All of these are enveloped by PSC's quality management program. Procurement, manufacturing, and stocking are controlled by inventory management software. Lightbands and their subsystems are tracked and completely traceable using their purchase order, serial number, or lot number. Just like in testing at PSC, manufacturing is done in teams. Two engineers sign-off on steps in manufacturing procedures (one acts as the technician, the other as quality assurance) and three engineers execute a Build Complete Review (BCR) as the final step in the completion of the manufacturing procedures. PSC writes, executes and approves manufacturing procedures. PSC also takes any corrective action after required customer notification if anomalies arise. The customer-furnished wiring harness is not included in the manufacturing of a Lightband.

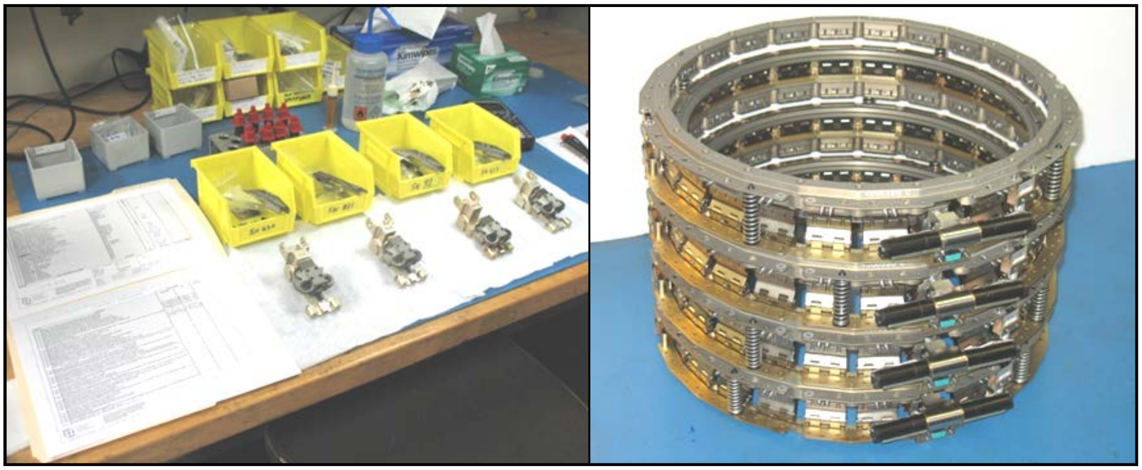


Figure 17-1: Lightband assembly at PSC

Figure 17-2: PSC's flight hardware assembly clean room

18. Acceptance Testing

PSC completes three standard acceptance tests (Vibration, Thermal Vacuum, and Separation Reliability) on standard flight Lightbands prior to delivery. This is part of PSC's quality assurance plan. EDU Lightbands do not go through standard acceptance tests. Instead, they are put-through approximately 5 bench-top operation cycles. Just like during assembly, all testing is performed by a team of PSC engineers. Two engineers sign-off on individual steps in testing procedures (one acts as the test director, the other as quality assurance) and three engineers execute a Test Complete Review (TCR) as the final step in the completion of the test procedures.

The Lightband is tested as "a unit" with respect to the definition in MIL-STD-1540. However, PSC's testing of the Lightband does not include the customer's wiring harness, which as noted earlier can weigh as much as or more than the Lightband. GSE Transition Rings are fastened to the Lightband during testing to mimic flight-like structural, thermal, and dynamic boundary conditions.

PSC writes, executes, and approves all test plans. PSC also takes any corrective action if anomalies arise after required customer notification. If requested, customers are supplied the test plans prior to test start. Prior to these tests, PSC completes several bench-top separation operations in order to tune-in the preload force of the Retaining Ring. There is no fixed sequence for these tests. Generally, customers are permitted to send one person to attend all testing at PSC. Arrangements must be made with PSC in advance if a customer representative is to attend a test.

Event	Standard or Custom?	Typical Number of Separations Performed
Bench-top separation	Standard	5
Vibration Test	Standard	1
Thermal Vacuum Test	Standard	1
Separation Reliability Test	Standard	5-10
Strength Test	Custom	1
Shock Test	Custom	1
Total (excluding custom tests)		12-17

Table 18-1: Standard test operations summary

18.1 Standard Acceptance Tests

Each test in this section is performed on every flight Lightband built by PSC. The test parameters default to those shown herein. Any adjustment to these parameters is considered custom work.

18.1.1 Random Vibration Test

Location: Qualified Vibration Test Facility in DC-metro area
Objective: Verify workmanship
Test Description: During this test, the test item will be exposed to a controlled random vibration profile in three orthogonal axes. Upon completion of vibration, the test item will be separated and then formally inspected to verify that it still operates nominally.
Standard Levels: Figure 18-2 defines the nominal acceptance test random vibration profile. These values are derived from *MIL-STD-1540-E Test Requirements for Launch, Upper-Stage, and Space Vehicles (SMC-TR-06-11).*
Number of separations: One (1) following the last of three axes of vibration

WARNING: These vibration levels shall not be applied to the Lightband when the Lightband is supporting a substantial mass without carefully considering the effects of resonance and structural impedance. The prescribed environment below is for the Lightband alone. When the Lightband is supporting a structure, engineers must determine how the vibration environment will generate line loading and how much of the Lightband's fatigue life will be consumed.

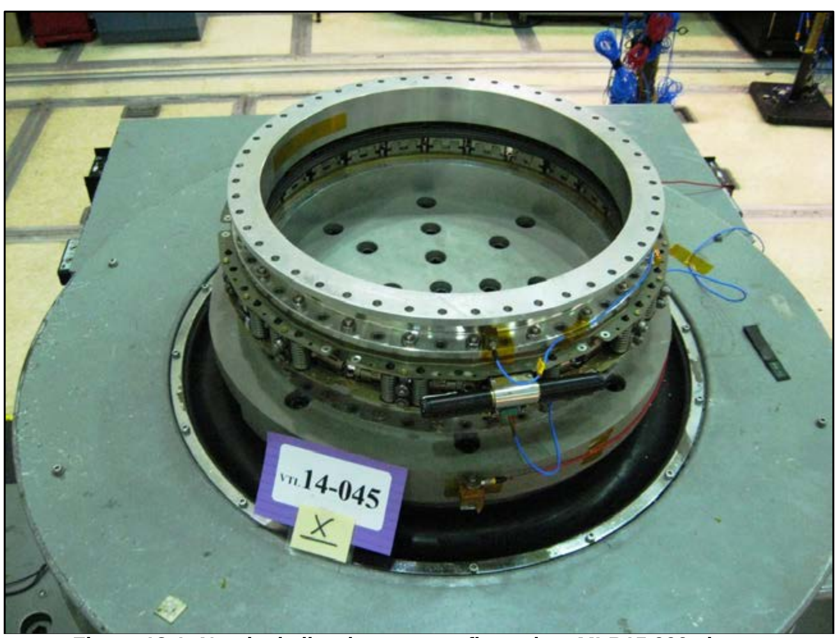


Figure 18-1: Nominal vibration test configuration, MLB15.000 shown

Random Vibration Testing

Source Document(s): PSC Document 2000785E User's Manual for Mark II Lightband, MIL-STD-1540 E

Test Objective: Demonstrate that the test item operates nominally after vibration loading

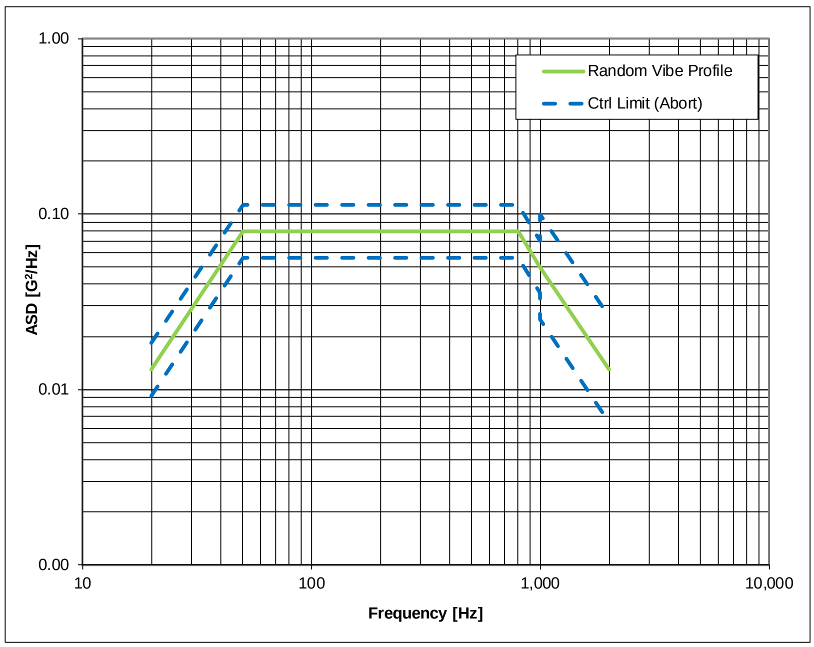
Test Complete Criteria:
1. The required random vibration profiles are applied to the test item in the specified directions for the specified durations.
2. The test item separates nominally after being exposed to all random vibration profiles.
3. The test item is inspected IAW PSC Document 2001066 “MkII MLB Inspection Report” upon completion of vibration exposure.
4. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

Notes:
(1) In a separation, springs elongate at least 0.7 inches, in an initiation, springs elongate 0.0 inches
(2) Control bandwidths may be combined for tolerance evaluation purposes.
(3) If additional accelerometers are added during test, they shall follow the same naming convention wherein C# signifies control and R# signifies response.
(4) Narrow Bandwith Exceedance tolerance is the maximum width that a control signal may exceed the control tolerance and still be considered acceptable.

Test Facility Data Transfer Requirements
Test Facility shall provide the following data
Sine Sweeps: Tabulated data and plots of the FRF (Magnitude and Phase). Plots shall overlay pre and post sweeps.
Random: Tabulated data and plots of the PSD profiles.

Random Vibration Profile						
Freq. [Hz]	ASD [G^2/Hz]	dB	OCT	Slope [dB/OCT]	AREA	G_{rms}
20	0.0130	*	*	*	*	*
50	0.0800	7.89	1.32	6.0	1.25	1.1
800	0.0800	0.00	4.00	0.0	61.25	7.8
2,000	0.0130	-7.89	1.32	-6.0	99.91	10.0

Random Vibration Tolerances			
Freq. [Hz]	Random Vibration Profile ASD [G^2/Hz]	Upper Ctrl Limit ASD [G^2/Hz]	Lower Ctrl Limit ASD [G^2/Hz]
20	0.0130	0.018	0.009
50	0.0800	0.113	0.057
800	0.0800	0.113	0.057
1000	0.0500	0.071	0.035
1000	0.0500	0.100	0.025
2000	0.0130	0.026	0.007



Pre-Random Vibe Ramp-Up		
Level [dB]	Duration [s]	Purpose
-6	≥15	Verify control strategy
-3	≥15	Verify control strategy

EDE Parameters		
Parameter	Value	Tolerance
Overall [G_{rms}]	10.0	±1.0
Duration per axis [sec]	60	+10/-0%
Axes tested [-]	X, Y, Z	-
Control Strategy [-]	Max	-
Ctrl tolerance, 10-1000 Hz [dB]	1.5	-
Ctrl tolerance, >1000 Hz [dB]	3.0	-
Max Ctrl. Bandwidth [Hz]	5	-
NBE Tol, 20-100 [Hz] (4)	10	-
NBE Tol, 100-1000 [Hz] (4)	10% midband freq.	-
NBE Tol, 1000-2000 [Hz] (4)	100	-
Crtl. Accel Crosstalk Upper Limit [G_{rms}]	In-axis input level	-
Random vibe DOF per channel [-]	120	±20
Data Sampling Rate [Hz]	5,000	minimum

Accelerometer Parameters				
Accel. Name (3)	Accel. Designation	Accel. Type	Accel. Planar Location	Accel Axial Location
C1	Control	Triaxial	Underside of top flange of lower TR	Along $+Y_{LB}$
C2	Control	Triaxial	Underside of top flange of lower TR	At test director's discretion. Default to Along $+Z_{LB}$.
R1	Response	Triaxial	Topside of lower flange of upper transition ring	Along $+Y_{LB}$

Functional Test Following Vibration		
Operation (1)	Voltage [V]	Motor(s) Powered
Separation	28.0	Both

Figure 18-2: Standard random vibration test requirements

18.1.2 Thermal-Vacuum Test

Location: PSC
Objective: Verify time-to-separate at temperature and pressure extremes
Test Description: During this test, the test item will be thermally cycled while inside a chamber that creates a partial vacuum as a simulation of in-flight conditions. At the last cycle's extreme temperature, the Lightband will be deployed. Upon completion of cycling in partial vacuum, the test item will be removed from the chamber and formally inspected to verify that it still operates nominally.
Standard Levels: See Figure 18-3. Thermal dwell time has been specified as ≥10 minutes. A dwell in excess of 10 minutes is unnecessary because the Lightband is relatively conductive unlike, for example, an avionics box which may possess many structures that are poorly coupled to the thermal sink.
Number of separations: One (1) at the end of thermal cycling.

Thermal-Vacuum Testing

Source Document(s): PSC Document 2000785E User's Manual for Mark II Lightband
Test Objective: Demonstrate that the test item operates nominally after thermal and pressure cycling
Test Complete Criteria: 1. The test item deploys nominally at each designated step.
2. The test item is inspected IAW PSC Document 2001066 "MkII MLB Inspection Report" upon completion of thermal vacuum cycling.
3. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.
Notes: (1) In a separation, springs travel at least 0.7 inches, in an initiation, springs travel 0.0 inches
(2) PSC does not guarantee pressure will remain below 1.0E-4 Torr at temperatures above +23°C for first several cycles
(3) A bake-out occurs after chamber is closed. Max bake-out temp shall be whichever is greater: required high temp or 70°C.

Thermal Cycle						
Max Pressure, excluding Bake-out [Torr] (2)	High Temp. [°C]	Low Temp. [°C]	Temp. Tolerance [°C]	No. of Thermal Cycles [-]	Dwell Time at High & Low Temp. [min]	Ctrl. Temp. Sensor Location [°C]
1.00E-04	59.0	-27.0	+/- 3.0	4	10.0	Motor A

Bake-out (3)	
Temp. [°C]	Duration [min]
70.0	60.0

Functional test while test item is in Thermal-Vacuum Chamber				
Operation (1)	Voltage [V]	Motor(s) Powered	Temp. [°C]	Operation After [thermal cycle]
Separation	24.0	A	-27.0	4

First Cycle Temp.
Low

Temperature Sensors				
Sensor No.	Sensor Type	Location	Control Sensor? [Y/N]	Required? [Y/N
R01	RTD	Motor A	Y	Y
T01	T-couple	Lower Ring	N	Y
T02	T-couple	-	-	N
T03	T-couple	-	-	N
T04	T-couple	-	-	N
T05	T-couple	-	-	N
T06	T-couple	-	-	N
T07	T-couple	-	-	N
T08	T-couple	-	-	N

Figure 18-3: Standard Thermal Vacuum test requirements

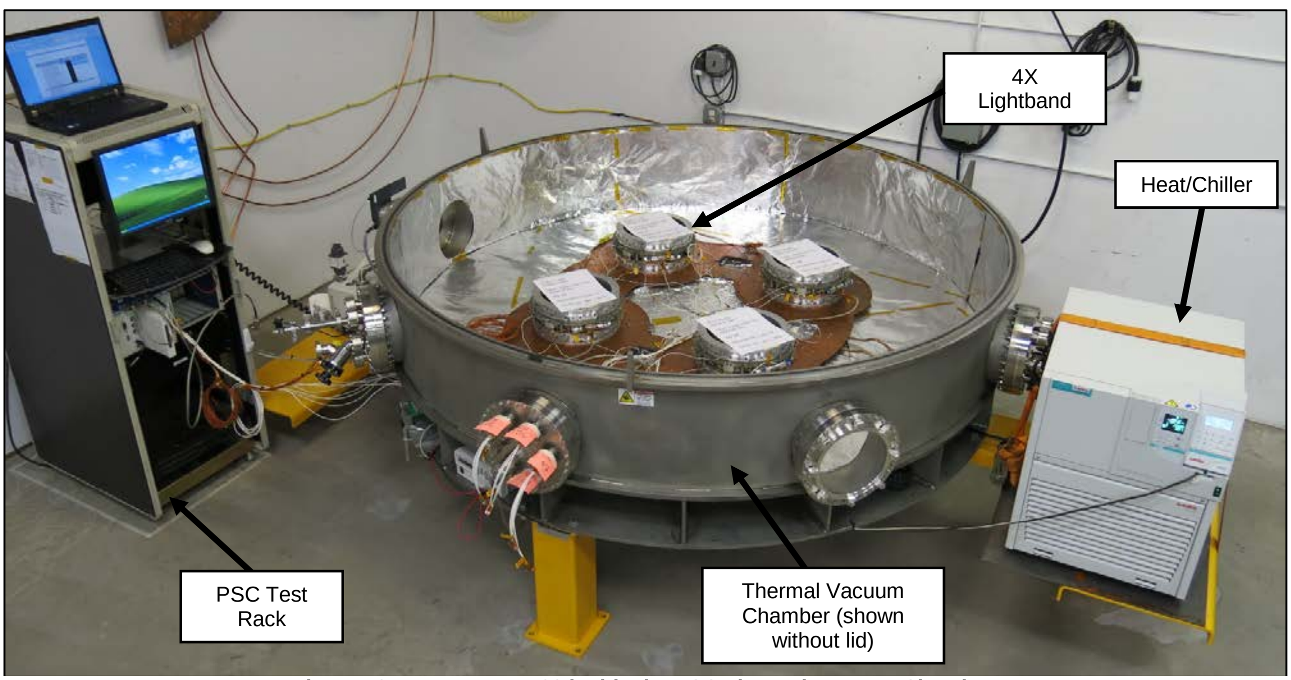


Figure 18-4: 4X MLB11.732 inside the PSC Thermal Vacuum Chamber

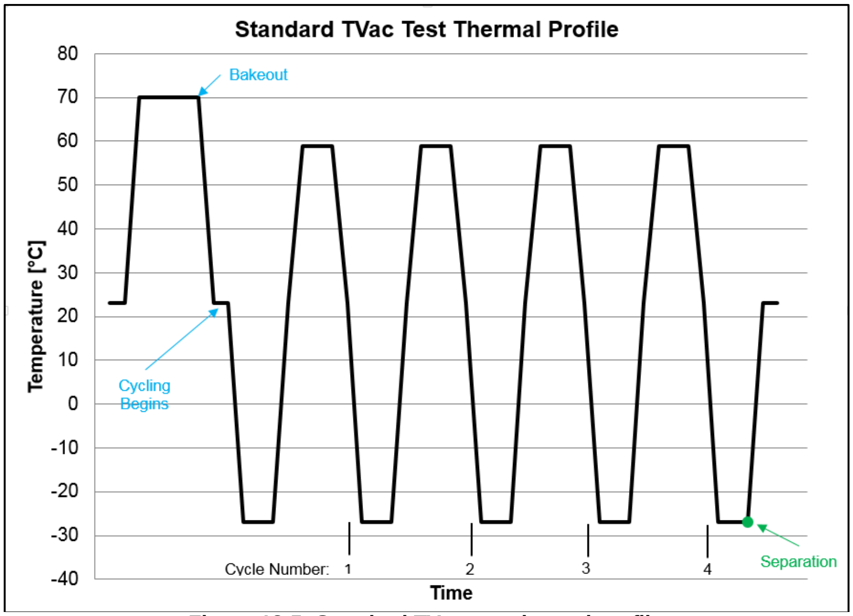


Figure 18-5: Standard TVac test thermal profile

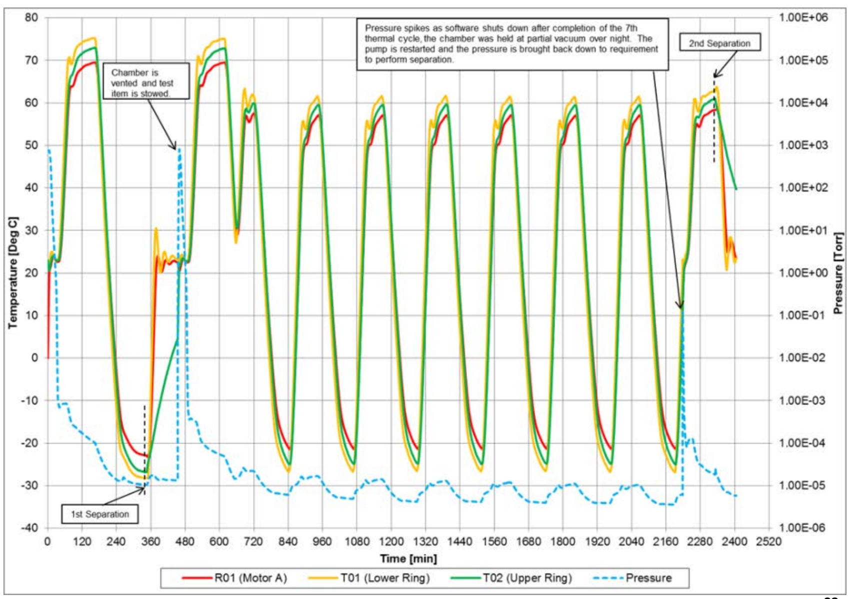


Figure 18-6: Sample data from a TVac test with more cycles than a standard test[28]

[28] Source: PSC Document 2002303-.

18.1.3 Separation Reliability Test

Location: PSC
Objective: Verify separation velocity, time-to separate, time to initiate, rotation rates and repeatability
Test Description: During this test, the test item is repeatedly separated on a 5 degree-of-freedom test fixture. For each separation, the separation velocity and rotation rates of the separating half of the fixture are measured along with the standard operation data such as motor current draw and time to initiate. If necessary, the configuration and quantity of Separation Springs may be modified to meet separation velocity and rotation rate requirements. Upon completion of 5 consecutive separations where all requirements are met, the test item is formally inspected to verify that it still operates nominally.
Standard Separation Reliability tests do not account for any center of mass offsets in the Y_{LB} or Z_{LB} axes. Performing a Separation Reliability test with anything other than standard levels in Table 18-2 is classified as a custom test and will warrant additional cost and schedule duration.
Standard Levels: See Table 18-2
Predicted In-Flight Levels Analysis: Because Separation Reliability tests cannot identically match flight mass and CG values, PSC provides analytical predictions of flight separation velocity and rotation rates based on test results in the delivered test report.

Parameter	Test Value	Tolerance	Units
Payload mass:	Standardized value determined by diameter. See Table 18-3.	See Table 18-3.	lbs.
Rotation rates for mass ≤ 200 lbs.	0.0	±5.0	deg/s
Rotation rates for mass >200 lbs.	0.0	±1.0	deg/s
Separation velocity:	Customer requirement	Customer requirement	ft/s
CM_{XLB}:	Standardized value determined by diameter. See Table 18-3.	See Table 18-3.	in
CM_{YLB}:	0.0	±0.05	in
CM_{ZLB}:	0.0	±0.05	in
Number of separations	5	+5-/0	-

Table 18-2: Standard separation reliability test parameters

MLB Diameter [-]	Separating Mass [lb]	Separating Mass Tol. [lb]	CG_X [in]	CG_X Tol. [in]	MOI_{XLB} [lb*in^2]	MOI_{YLB} [lb*in^2]	MOI_{ZLB} [lb*in^2]	MOI Tol. [lb*in^2]
8.000	142	±25%	14.8	±0.5	5,363	22,489	25,396	±10%
11.732	142	±25%	14.8	±0.5	5,457	23,235	26,134	±10%
15.000	245	±25%	14.8	±1.0	10,355	25,305	22,139	±10%
19.848	478	±25%	17.8	±1.0	39,604	76,992	99,112	±10%
23.250	222	±25%	14.8	±1.0	21,201	60,102	61,836	±10%
24.000	661	±25%	23.0	±1.0	147,047	291,624	224,907	±10%
31.600	842	±25%	26.3	±2.0	197,200	429,600	406,500	±10%
38.810	479	±25%	29.7	±2.0	152,184	160,415	44,724	±10%

Table 18-3: Standard Separation Reliability Separating Mass, CG_X, & moment of inertia values

Separation Reliability Testing

Source Document(s): PSC Document 2000785 MkII MLB User Manual

Test Objective: Demonstrate that the test item separates reliably

Test Complete Criteria:
1. The test item meets all requirements defined in the test plan over 10 consecutive separations.
2. The test item is inspected IAW PSC Document 2001066 “MkII MLB Inspection Report” upon completion of test.
3. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

Notes:
(1) Test fixture limitations can affect attainable inertia values. Tolerances will be specified on a best effort basis.
(2) Dependent on test SV mass. Ensure minimum Flight Delta V requirement will be met.
(3) Spring energy [J]: 1.020
(4) Spring efficiency [-]: 0.9

Test Parameters				
Parameter		Test Config.	Test Tolerance	Remark
Payload (SC) Mass [lb_m]		See Table 18-3	See Table 18-3	
Final Stage (FS) Mass [lb_m]		1.00E+06	-	FS simulated by stiff, static fixture
Separation Velocity [ft/sec] (2)		Requirement	Requirement	
Inertia [lb_m*in^2] about CM (1)	X_{LB}	See Table 18-3	See Table 18-3	Shall not be measured, provided by analysis
	Y_{LB}	See Table 18-3	See Table 18-3	Shall not be measured, provided by analysis
	Z_{LB}	See Table 18-3	See Table 18-3	Shall not be measured, provided by analysis
CM [in] (measured from MLB origin)	X_{LB}	See Table 18-3	See Table 18-3	
	Y_{LB}	0.0	±0.05	Shall not be measured. Ensured via fixture precision.
	Z_{LB}	0.0	±0.05	Shall not be measured. Ensured via fixture precision.
Rotation Rates [deg/sec]	X_{LB}	0.0	±1.0	
	Y_{LB}	0.0	±1.0	
	Z_{LB}	0.0	±1.0	
Consecutive Test Cycles in Tol. [-]		5	+5/-0	
Motor(s) Powered Duration (Deploy) [s]		0.085	±0.050	
Acceptance Trials Commanded Voltge [V]		1) 28 2) 28 3) 28 4) 32 5) 24	-	
Acceptance Trials Motors Powered [A, B, Both]		1) Both 2) A 3) B 4) A 5) B	-	

Figure 18-7: Standard separation reliability test requirements for a separating mass >200 lbs.

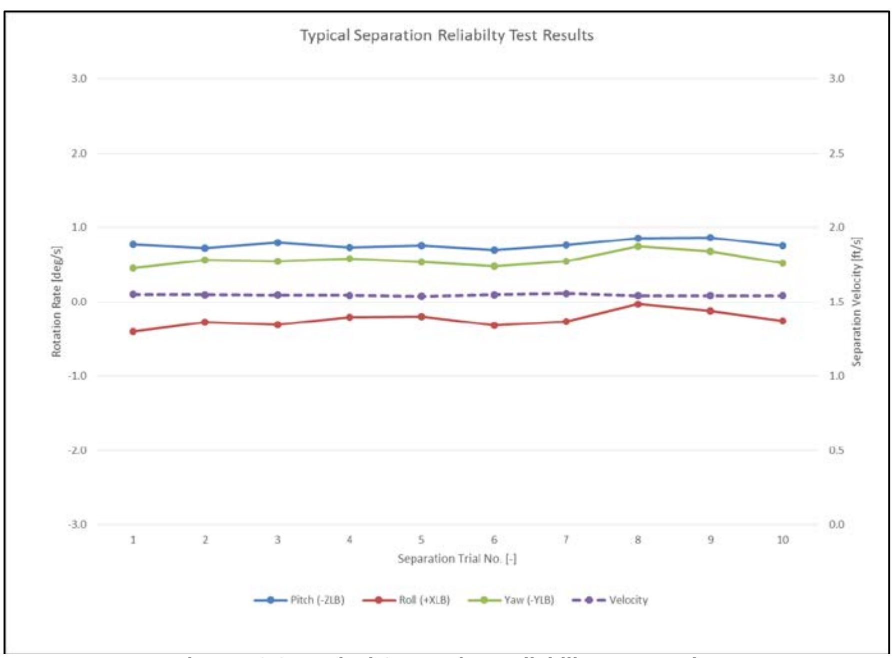


Figure 18-8: Typical Separation Reliability test results

Reference Data						Motor Parameters							Measured Results				Analysis		
Trial No.	Sep. Spring Qty.	Cfg. No.	.lvm File Name	Pre-Stow Weight [lb]	Post-SFF Weight [lb]	Motors Powered [-]	Cmmded. Voltage [V]	Ch A Peak Voltage [V]	Ch B Peak Voltage [V]	Ch A Peak Current [A]	Ch B Peak Current [A]	Motors Powered Duration[3] [s]	Pitch (About $-Z_{LB}$ Axis) [deg/s]	Yaw (About $-Y_{LB}$ Axis) [deg/s]	Roll (About $+X_{LB}$ Axis) [deg/s]	Velocity [ft/s]	Kinetic Energy [J]	Predicted Flight Velocity[2] [m/s]	Predicted Flight Velocity[2] [ft/s]
Tuning Trials																			
1	10	1	deploy_001	187.4	183.8	A&B	28.0	27.146	27.142	1.166	1.210	0.074	1.020	0.150	-0.620	1.470	8.53	0.455	1.494
2	11	2	deploy_002	188.7	188.8	A&B	28.0	27.368	27.377	2.191	2.212	0.071	0.953	0.529	-0.870	1.534	9.36	0.477	1.564
3	11	2	deploy_003	190.1	188.1	A&B	28.0	27.314	27.392	2.190	2.487	0.072	1.070	0.581	-0.761	1.550	9.62	0.483	1.586
Acceptance Trials																			
1	11	2	deploy_001	190.0	187.7	A&B	28.0	27.305	27.290	2.193	2.228	0.071	0.773	0.454	-0.400	1.549	9.61	0.483	1.585
2	11	2	deploy_002	190.1	187.2	A	28.0	27.083	21.338	2.426	0.603	0.097	0.720	0.566	-0.271	1.548	9.60	0.483	1.585
3	11	2	deploy_003	190.1	186.9	B	28.0	22.791	27.065	2.030	2.502	0.092	0.794	0.546	-0.308	1.546	9.57	0.482	1.582
4	11	2	deploy_004	190.1	187.6	A&B	32.0	31.609	31.209	2.500	2.522	0.059	0.731	0.582	-0.208	1.544	9.55	0.482	1.580
5	11	2	deploy_005	190.1	187.7	A	32.0	30.994	24.927	2.651	0.636	0.079	0.758	0.537	-0.199	1.538	9.47	0.480	1.573
Comments											Mean[1]	0.080	0.755	0.537	-0.277	1.545	9.56	0.48	1.581
1) For acceptance trials only.											Minimum[1]	0.059	0.720	0.454	-0.400	1.538	9.47	0.48	1.573
2) Assumes the following masses [lb]											Maximum[1]	0.097	0.794	0.582	-0.199	1.549	9.61	0.48	1.585
FS	1361	SC	88				Pitch ($-Z_{LB}$)	16	lb*in^2		Standard Deviation[1]	0.015	0.030	0.050	0.082	0.005	0.06	0.00	0.005
3) Time from power on until either deploy limit switch initia							Yaw ($-Y_{LB}$)	43,377	lb*in^2		Allowable Maximum	0.135	1.500	1.500	2.300	1.484	N/A	0.454	1.490
4) Sep. Arm inertia about CM aligned with MLB coords:							Roll ($+X_{LB}$)	38,992	lb*in^2		Allowable Minimum	0.035	-1.500	-1.500	-2.300	1.627	N/A	0.498	1.634

Figure 18-9: Example test results from separation reliability test conducted on a standard MLB15.000

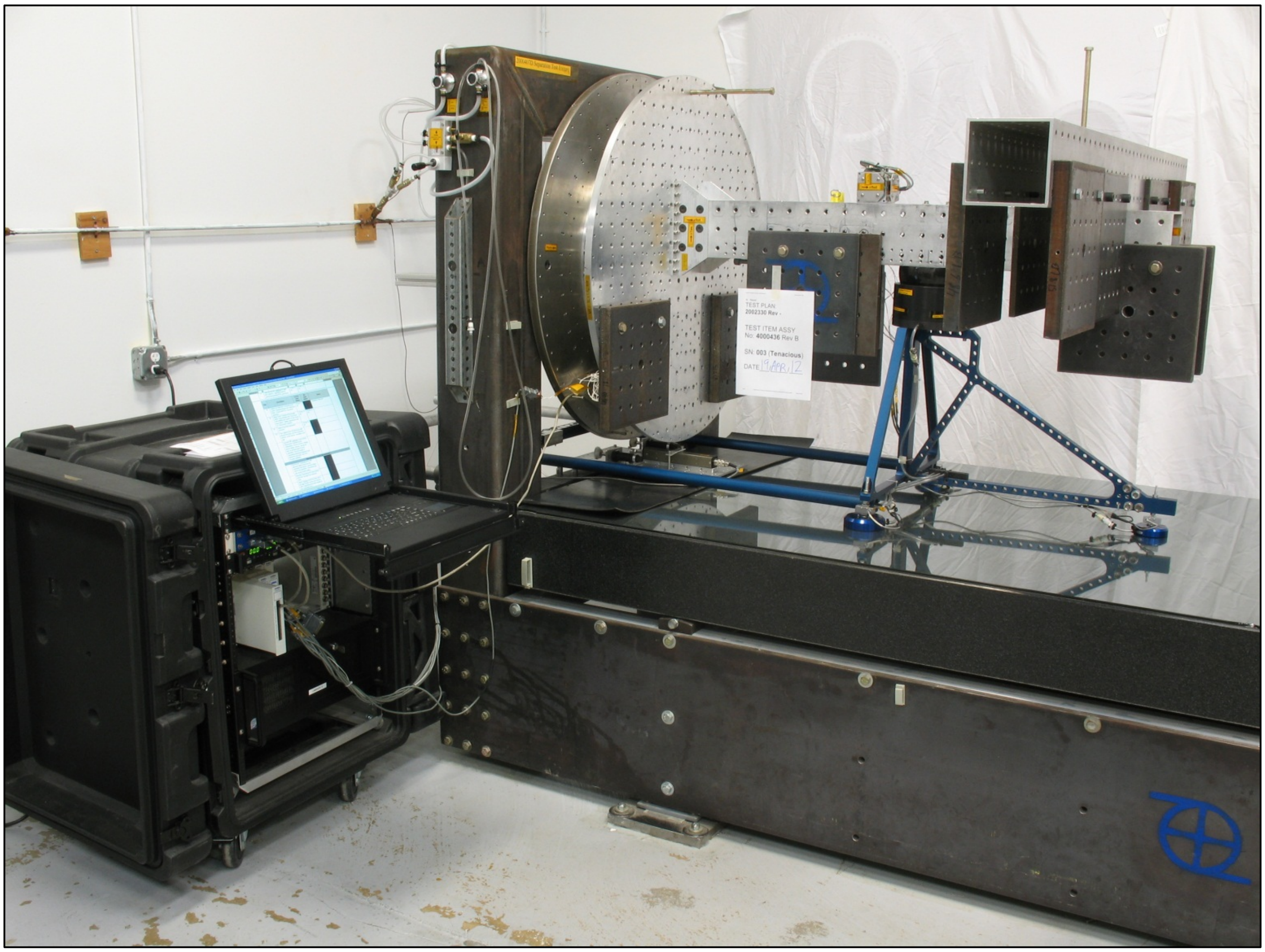


Figure 18-10: PSC’s Separation reliability fixture

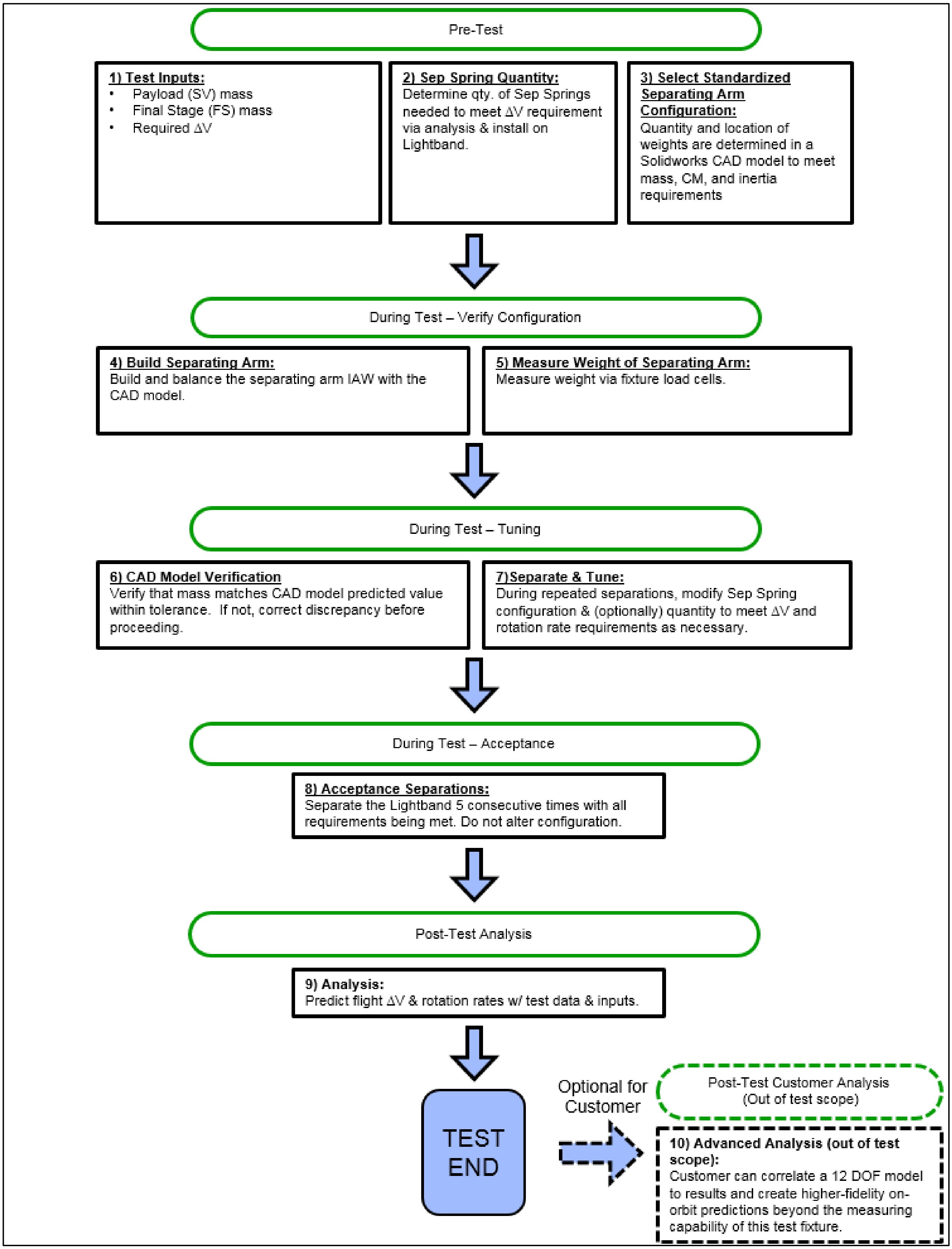


Figure 18-11: Nominal separation reliability test flow

18.2 Custom Acceptance Tests

The following acceptance tests are not standard and are not performed for all flight Lightbands. Criteria that determine the need for these tests are stated herein. PSC reserves the right to perform these tests on any flight Lightband if desired.

Any Lightband that requires any of these tests shall be considered custom. Custom Lightband incur additional cost and schedule duration over Standard Lightbands.

18.2.1 Strength Test

Location: PSC or Qualified Vibration Test Facility in DC-metro area
Objective: Verify strength of the Lightband
Test Fixture: PSC Strength Test Fixture or software-controlled vibration table
Test Method: Quasi-static loading or sine burst (to be selected by PSC based on engineering judgement)
Test Description: During this test, the test item shall be exposed to quasi-static loading or sine burst loading that is intended to simulate in-flight acceleration forces in the set-for-flight configuration. Each combination of loads is known as a load case. In some sine burst tests, the loads shall be applied independently along each axis. Upon completion of all load cases, the test item will be separated and then formally inspected to verify that it still operates nominally.
Standard Levels: Half of maximum loads shown in Table 5-1. Lateral and axial loads applied independently. For quasi-static tests, the load is held at maximum level for at least 60 seconds. Load is applied in approximately 20% increments.
Test Tolerances: Lower limit shall be customer minimum customer load requirement (or standard level given above). Upper limit shall be the maximum capability given in Table 5-1 to account for intra-increment peaking.
Number of separations: One (1) following all load cases.
Criteria for performing test:

1) The unit demonstrates an axial line load margin of safety of less than +1.0 or a lateral line load margin of safety on yield of less than +1.0 in pre-test analysis.
   OR
2) The unit design is custom such that it uses materials in the load path that are different from those in Table 6-8.
   OR
3) The unit will not undergo a random vibration test to verify workmanship.

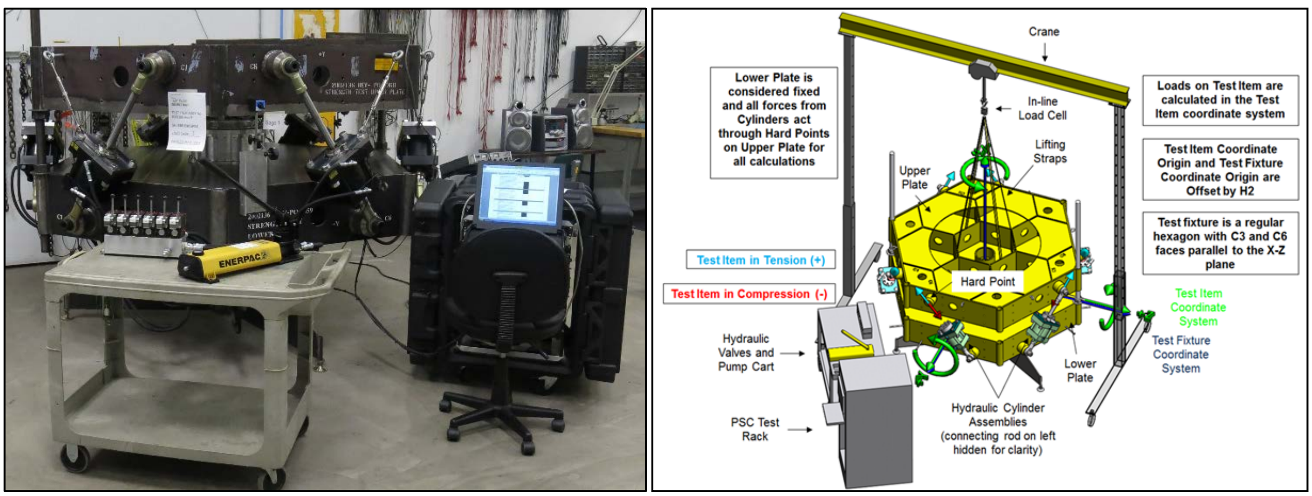


Figure 18-12: The PSC Strength Test Fixture

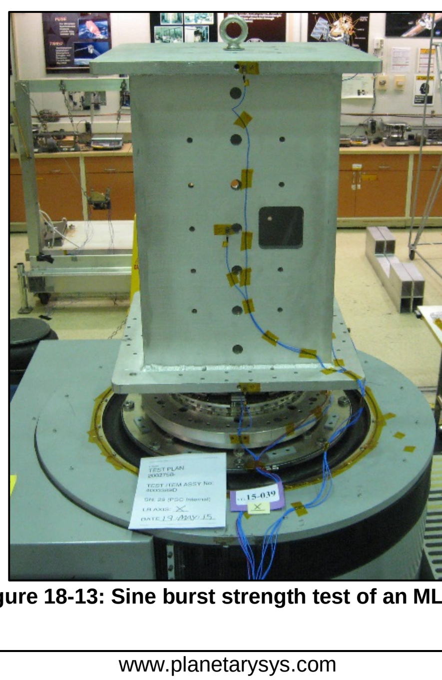


Figure 18-13: Sine burst strength test of an MLB15

Strength Testing

Source Document(s): PSC Document 2000785

Test Objective: Demonstrate that the test item operates nominally after quasi-static loading

Test Complete Criteria: 1. The required loads are applied to the test item.
2. The test item is inspected IAW PSC Document 2001066 “MkII MLB Inspection Report” upon completion of all load cases.
3. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

Notes: (1) Assumes CM_Y and CM_Z are zero. RSS of Y_{LB} and Z_{LB} load factors.
(2) In a separation, springs travel at least 0.7 inches, in an initiation, springs travel 0.0 inches.
(3) "-" is compression in test item.
(4) Applied through CM.
(5) See 2000785 User's Manual for MkII Lightband for criteria to determine if a strength test is required.
(6) Peak load target is 102.5% to ensure that 100% requirement is reached.

Load Application		
	Load Case 1	Load Case 2
F_{XLB} [lb_f]	Derived by customer requirement and Lightband diameter.	Derived by customer requirement and Lightband diameter.
F_{YLB} [lb_f]		
F_{ZLB} [lb_f]		
M_{XLB} [in*lb_f]		
M_{YLB} [in*lb_f]		
M_{ZLB} [in*lb_f]		
Peak Load Duratoin [s]	60	60
Max. Allowable Load [%]	105	105

Pre-test Analysis		
Load Case	Max. X_{LB} Line Load [lb_f/bolt] (Axial)	Max. Y_{LB} or Z_{LB} Line Load [lb_f/bolt] (Shear)
1	Derived by customer requirement and Lightband diameter.	Derived by customer requirement and Lightband diameter.
2		
3		
4		
Allowable [lb_f/bolt]	1,880	774
Max Actual [lb_f/bolt]	Derived	Derived
Margin [-]	Derived	Derived
Margin = (Allowable/Max Actual) - 1		

Load Application (6)		
Step	Load Percentage [%]	Increment or Decrement ?
1	0	Increment
2	20	Increment
3	40	Increment
4	60	Increment
5	80	Increment
6	102.5	Increment
7	80	Decrement
8	60	Decrement
9	40	Decrement
10	20	Decrement
11	0	Decrement

Functional test following all load cases		
Operation (2)	Voltage [V]	Motor(s) Powered
Separation	28.0	Both

Deflection Gage Placement		
Gage	Position	Orientation
1	$+Y_{fixture}$ Axis	$-Y_{fixture}$ Axis
2	$+Z_{fixture}$ Axis	$-X_{fixture}$ Axis
3	$-Z_{fixture}$ Axis	$-X_{fixture}$ Axis

Figure 18-14: Example of custom strength test requirements (performed as quasi-static loading)

18.2.2 Shock Test

Location: PSC
Objective: Prove that the test item can operate nominally after being exposed to required shock profiles.
Test Description: Then the test item will be exposed to the required shock profiles. Upon completion of shock exposure, the test item will be separated and then formally inspected to verify that it still operates nominally.
Standard Levels: Shock applied to the Lightband is shown in Figure 18-15. These values are derived from *MIL-STD -1540-E Test Requirements for Launch, Upper-Stage, and Space Vehicles (SMC-TR-06-11).*
Number of separations: One (1) following all load cases.
Criterion for performing test: The flight Lightband is expected to be exposed to a shock spectrum not previously experienced by a Lightband. PSC will determine whether this criterion is true during the contract negotiations process.

Shock Testing

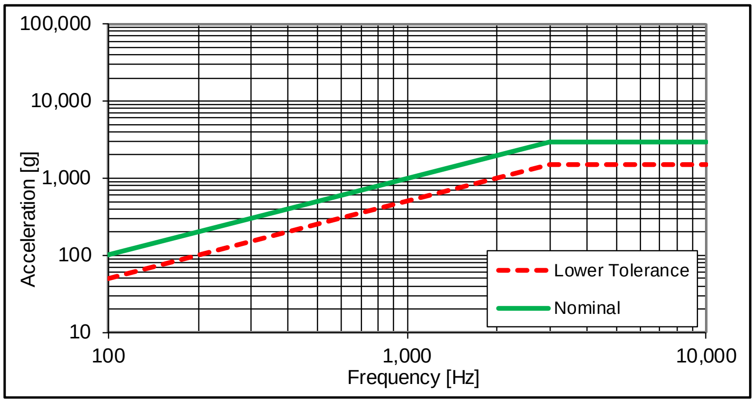
Source Document(s): PSC Document 2000785

Test Objective: Measure the maximum shock that the test item produces
Demonstrate that the test item operates nominally after exposed to shock loads

Test complete criteria: 1. The required shock profiles are applied to the test item in the specified axes.
2. Shock produced by the test item is measured.
3. The test item separates nominally after being exposed to required shock profiles.
4. The test item is inspected IAW PSC Document 2001066 “MkII MLB Inspection Report” upon completion of shock exposure.
5. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

Notes: (1) In a separation, springs travel at least 0.7 inches, in an initiation, springs travel 0.0 inches
(2) Test Spectrum must also be 50% above the Nominal SRS
(3) Upper tolerance is a guideline not a requirement
(4) A trial is defined as meeting the Shock Requirement in that axis (ie. one impact could meet the shock in all 3 axes).
(5) See 2000785 User's Manual for MkII Lightband for criteria to determine if a shock test is required.

Applied Acceleration [g]		
Freq. [Hz]	Lower Tolerance	Nominal
100	50	100
600	300	600
3,000	1,500	3,000
10,000	1,500	3,000



Shock Parameters	
Shock Spectrum Type [-]	MaxiMax
Axis of Excitation	Trials (4)
X	3
Y	3
Z	3

Functional Test Following All Trials		
Operation (1) [Separation or Initiation]	Voltage [V]	Motor(s) Powered [A, B, Both]
Separation	28.0	Both

Accelerometer Locations				
Accel. Name	Accel. Designation	Accel. Type	Accel. Planar Location	Accel Axial Location
C1	Control	Triaxial	Lower interface	Along $+X_{LB}$
C2	Control	Triaxial	Lower interface	Along $+Z_{LB}$

Test Stack		
Location	Item	Weight [lb]
Bottom	Vibe Plate	>30
…	Transition Ring	Variable
…	Lightband	Variable
Top	Transition Ring	Variable

Figure 18-15: Example of custom shock test requirements

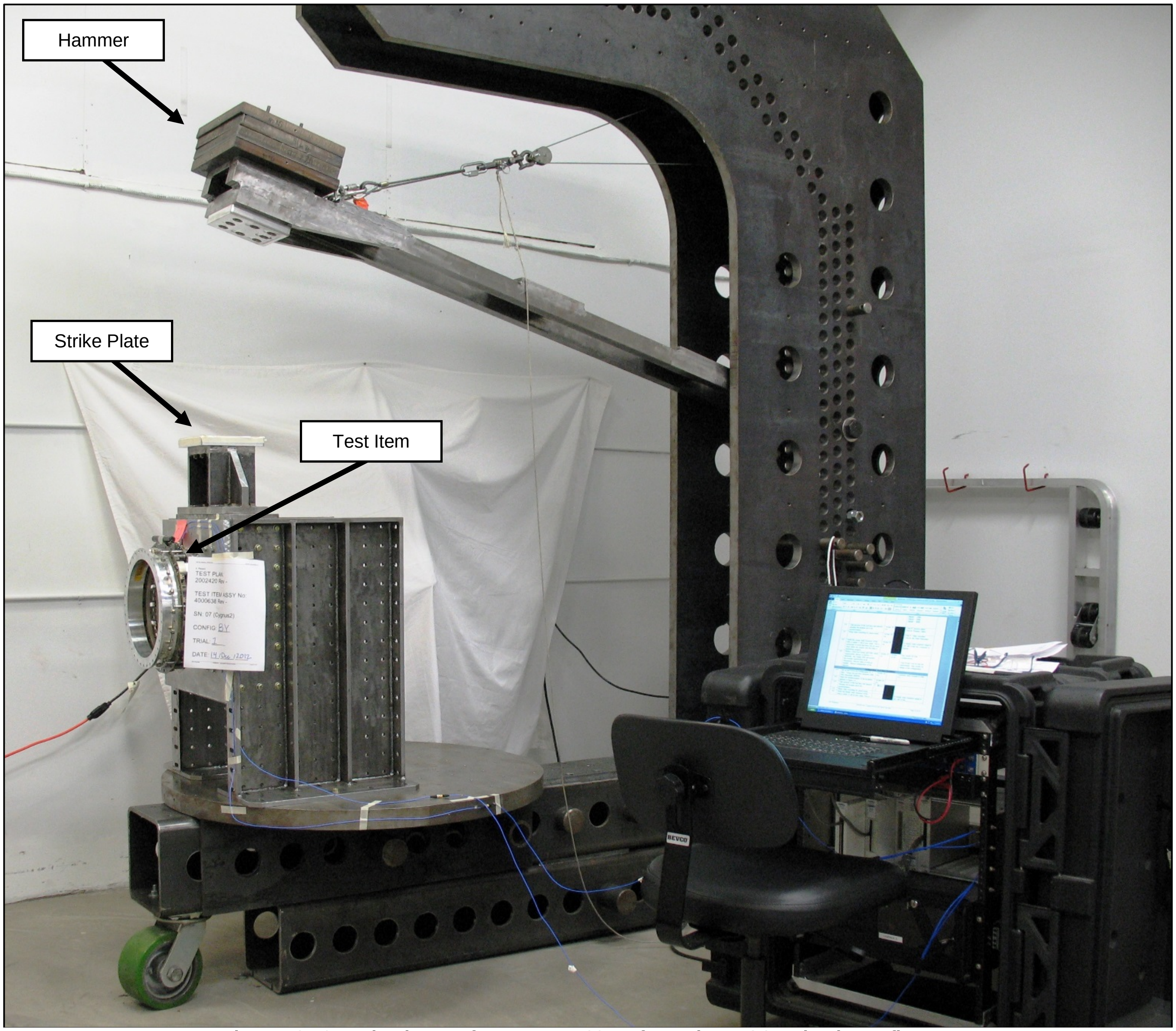


Figure 18-16: A shock test of an MLB11.732 performed on PSC's shock test fixture

19. Qualification Testing

Various diameters of Lightbands have received qualification environmental testing on multiple occasions. Qualification tests of Lightband diameters shown in Table 5-1 are generally not required and shall be considered custom work. This section is intended as a reference to present proven limits of the Lightband during previous environmental qualification tests.

19.1 Random Vibration Qualification Test

Tested vibration parameters of a 15 inch diameter Lightband are shown in Figure 19-1.

WARNING: These vibration levels should not be applied to the Lightband when the Lightband is supporting a substantial mass without carefully considering the effects of resonance and structural impedance. The prescribed environment below is for the Lightband alone. When the Lightband is supporting a structure, engineers must determine how the vibration environment will generate line loading and how much of the Lightband's fatigue life will be consumed.

Qualification Random Vibration Testing

Source Document(s): PSC Document 2002080E

Test Objective: Demonstrate that the test item operates nominally after vibration loading

Test Complete Criteria:
1. The required random vibration profiles are applied to the test item in the specified directions for the specified durations.
2. The test item separates nominally after being exposed to all random vibration profiles.
3. The test item is inspected IAW PSC Document 2001066 "MkII MLB Inspection Report" upon completion of vibration exposure.
4. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

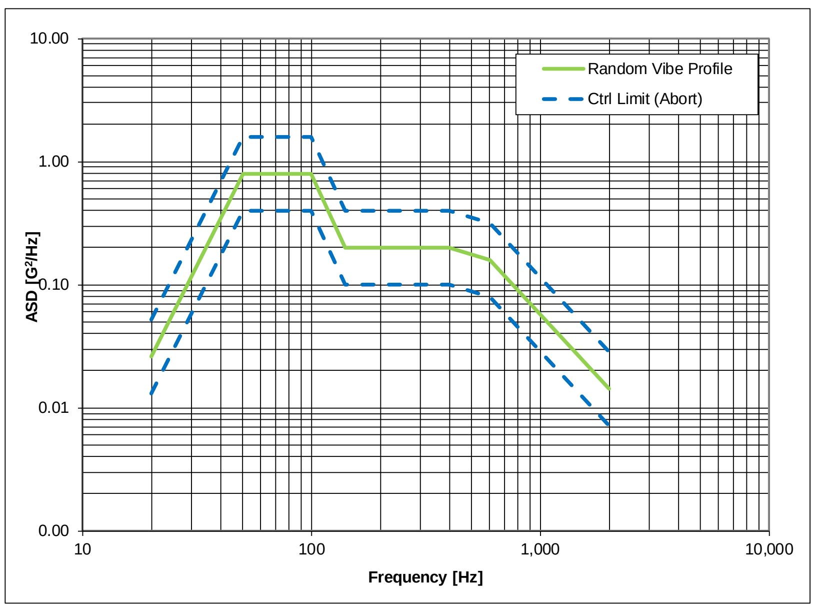
Notes:
(1) In a separation, springs elongate at least 0.7 inches, in an initiation, springs elongate 0.0 inches
(2) Control bandwidths may be combined for tolerance evaluation purposes.
(3) If additional accelerometers are added during test, they shall follow the same naming convention wherein C# signifies control and R# signifies response.
(4) Narrow Bandwith Exceedance tolerance is the maximum width that a control signal may exceed the control tolerance and still be considered acceptable.

Random Vibration Profile

Freq. [Hz]	ASD [G^2/Hz]	dB	OCT	Slope [dB/OCT]	AREA	G_{rms}
20	0.0260	*	*	*	*	*
50	0.7960	14.86	1.32	11.24	8.30	2.88
100	0.7960	0.00	1.00	0.00	48.10	6.94
140	0.1990	-6.02	0.49	-12.40	64.68	8.04
400	0.1990	0.00	1.51	0.00	116.42	10.79
600	0.1590	-0.97	0.58	-1.67	151.80	12.32
2,000	0.0143	-10.46	1.74	-6.02	218.56	14.78

Random Vibration Tolerances

Freq. [Hz]	Random Vibration Profile ASD [G^2/Hz]	Upper Ctrl Limit ASD [G^2/Hz]	Lower Ctrl Limit ASD [G^2/Hz]
20	0.0260	0.052	0.013
50	0.7960	1.588	0.399
100	0.7960	1.588	0.399
140	0.1990	0.397	0.100
400	0.1990	0.397	0.100
600	0.1590	0.317	0.080
2,000	0.0143	0.029	0.007



Pre-Random Vibe Ramp-Up

Level [dB]	Duration [s]	Purpose
-6	≥15	Verify control strategy
-3	≥15	Verify control strategy

EDE Parameters

Parameter	Value	Tolerance
Overall [G_{rms}]	14.8	±1.0
Duration per axis [sec]	180	+10/-0%
Axes tested [-]	X, Y, Z	-
Control Strategy [-]	Max	-
Control Tolerance (±) [dB]	3.0	-
Max Ctrl. Bandwidth [Hz]	20	-
NBE Tolerance (4)	100	-
Crtl. Accel Crosstalk Upper Limit [G_{rms}]	In-axis input level	-
Random vibe DOF per channel [-]	110	±10
Data Sampling Rate [Hz]	5,000	minimum

Figure 19-1: Previously-executed qualification random vibration test parameters[29]

[29] Source: PSC Document 2002080E

19.2 Thermal Vacuum Qualification Test

Tested thermal vacuum parameters of a 15 inch diameter Lightband are shown in Figure 19-2.

Qualification Thermal-Vacuum Testing

Source Document(s): PSC Document 2002305-

Test Objective: Demonstrate that the test item operates nominally after thermal and pressure cycling

Test Complete Criteria:
1. The test item deploys nominally at each designated step.
2. The test item is inspected IAW PSC Document 2001066 "MkII MLB Inspection Report" upon completion of thermal vacuum cycling.
3. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

Notes:
(1) In a separation, springs travel at least 0.7 inches, in an initiation, springs travel 0.0 inches
(2) PSC does not guarantee pressure will remain below 1.0E-4 Torr at temperatures above +23°C for first several cycles
(3) A bake-out occurs after chamber is closed. Max bake-out temp shall be whichever is greater: required high temp or 70°C.

Thermal Cycle						
Max Pressure, excluding Bake-out [Torr] (2)	High Temp. [°C]	Low Temp. [°C]	Temp. Tolerance [°C]	No. of Thermal Cycles [-]	Dwell Time at High & Low Temp. [min]	Ctrl. Temp. Sensor Location [°C]
1.00E-04	110.0	-46.0	+/- 4.0	4	10.0	Motor A

Bake-out (3)	
Temp. [°C]	Duration [min]
120.0	60.0

Figure 19-2: Previously-executed qualification TVac test parameters[30]

19.3 Strength Qualification Test

Tested strength parameters of a 15 inch diameter Lightband are shown in Figure 19-3.

Qualification Strength Testing

Source Document(s): PSC Document 2002319A

Test Objective: Demonstrate that the test item operates nominally after quasi-static loading

Test Complete Criteria:
1. The required loads are applied to the test item.
2. The test item is inspected IAW PSC Document 2001066 "MkII MLB Inspection Report" upon completion of all load cases.
3. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

Notes:
(1) Assumes CM_Y and CM_Z are zero. RSS of Y_{LB} and Z_{LB} load factors.
(2) In a separation, springs travel at least 0.7 inches, in an initiation, springs travel 0.0 inches.
(3) "-" is compression in test item.
(4) Applied through CM.
(5) See 2000785 User's Manual for MkII Lightband for criteria to determine if a strength test is required.
(6) Peak load target is 102.5% to ensure that 100% requirement is reached.

Load Application		
	Load Case 1	Load Case 2
F_{XLB} [lb_f]	3,000	-3,000
F_{YLB} [lb_f]	0	9,000
F_{ZLB} [lb_f]	9,000	0
M_{XLB} [in*lb_f]	0	0
M_{YLB} [in*lb_f]	-157,500	0
M_{ZLB} [in*lb_f]	0	-157,500
Peak Load Duration [s]	60	60
Max. Allowable Load [%]	105	105

Functional test following all load cases		
Operation (2)	Voltage [V]	Motor(s) Powered
Separation	28.0	Both

Pre-test Analysis		
Load Case	Max. X_{LB} Line Load [lb_f/bolt] (Axial)	Max. Y_{LB} or Z_{LB} Line Load [lb_f/bolt] (Shear)
1	1,875	750
2	1,875	750
Allowable [lb_f/bolt]	1,880	774
Max Actual [lb_f/bolt]	1,875	750
Margin [-]	0.00	0.03
Margin = (Allowable/Max Actual) - 1		

Deflection Gage Placement		
Gage	Position	Orientation
1	$+Y_{fixture}$ Axis	$-Y_{fixture}$ Axis
2	$+Z_{fixture}$ Axis	$-X_{fixture}$ Axis
3	$-Z_{fixture}$ Axis	$-X_{fixture}$ Axis

Load Application (6)		
Step	Load Percentage [%]	Increment or Decrement ?
1	0	Increment
2	20	Increment
3	40	Increment
4	60	Increment
5	80	Increment
6	102.5	Increment
7	80	Decrement
8	60	Decrement
9	40	Decrement
10	20	Decrement
11	0	Decrement

Figure 19-3: Previously-executed qualification strength test parameters[31]

[30] Source: PSC Document 2002305-
[31] Source: PSC Document 2002319A

19.4 Shock Qualification Test

Tested applied shock parameters on a 15 inch diameter Lightband are shown in Figure 19-4.

Qualification Shock Testing

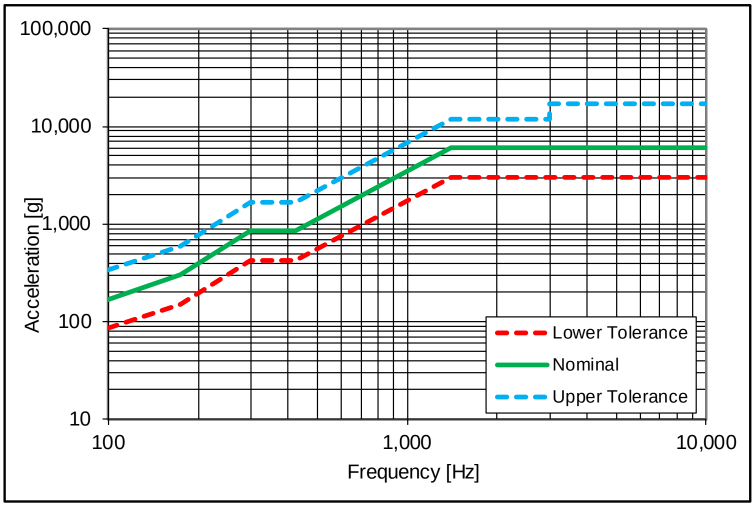
Source Document(s): PSC Document 2002081F

Test Objective: Measure the maximum shock that the test item produces
Demonstrate that the test item operates nominally after exposed to shock loads

Test complete criteria:
1. The required shock profiles are applied to the test item in the specified axes.
2. Shock produced by the test item is measured.
3. The test item separates nominally after being exposed to required shock profiles.
4. The test item is inspected IAW PSC Document 2001066 “MkII MLB Inspection Report” upon completion of shock exposure.
5. All attendees of the PSC-internal Test Complete Review (TCR) approve the test plan and results.

Notes: (1) In a separation, springs travel at least 0.7 inches, in an initiation, springs travel 0.0 inches
(2) Test Spectrum must also be 50% above the Nominal SRS
(3) Upper tolerance is a guideline not a requirement
(4) A trial is defined as meeting the Shock Requirement in that axis (ie. one impact could meet the shock in all 3 axes).
(5) See 2000785 User's Manual for MkII Lightband for criteria to determine if a shock test is required.

Applied Acceleration [g]			
Freq. [Hz]	Lower Tolerance	Nominal	Upper Tolerance
100	85	170	338
175	150	299	597
300	425	848	1,692
425	425	848	1,692
1,400	3,000	5,986	11,943
3,000	3,000	5,986	11,943
3,001	3,000	5,986	16,870
10,000	3,000	5,986	16,870



Shock Parameters	
Shock Spectrum Type [-]	MaxiMax
Axis of Excitation	Trials (4)
X	3
Y	3
Z	3

Functional Test Following All Trials		
Operation (1) [Separation or Initiation]	Voltage [V]	Motor(s) Powered [A, B, Both]
Separation	28.0	Both

Accelerometer Locations				
Accel. Name	Accel. Designation	Accel. Type	Accel. Planar Location	Accel Axial Location
C1	Control	Triaxial	Lower interface	Along $+X_{LB}$
C2	Control	Triaxial	Lower interface	Along $+Z_{LB}$

Test Stack		
Location	**Item**	**Weight [lb]**
Bottom	Vibe Plate	>30
…	Transition Ring	Variable
…	Lightband	Variable
Top	Transition Ring	Variable

Figure 19-4: Previously-executed qualification shock test parameters[32]

[32] Source: PSC Document 2002258-

20. Lightband Inspection

After assembly, each acceptance test, and before shipment, the Lightband goes through a standardized inspection procedure defined in PSC Document *2001066 Mk II MLB Inspection Report.* The purpose of the inspection is to characterize the condition of the Lightband in a consistent and quantifiable manner. Each subcomponent of the Lightband is examined and measured where applicable. The actions of this process are performed by the Test Director and independently verified by another PSC Engineer who acts as quality assurance. Inspections can be performed at any time.

This inspection shall be deemed successful if all of the responses shown in Table 20-1 are "yes". PSC reserves the right to pass a test item if two PSC engineers and either the Chief Engineer or President determine that a "no" inspection point is non-detrimental to the future operation of the Lightband. PSC also reserves the right to fail a test item even if the answers are all "yes" given the same criteria. Inspections are not limited to the items in Table 20-1 and additional items may be added at the inspector's discretion.

Sec-tion	Item No.	Item Description	Tech Date & Initials	QA Date & Initials	Item Result
MLB	1	Did the Lightband separate?			Choose an item.
Fasteners	2	Are all accessible fasteners in place?			Choose an item.
	3	Are all accessible fasteners tight (can only be loosened with tools?)			Choose an item.
	4	Is the staking on accessible fasteners not delaminated by more than 25% of any accessible fastener's circumference?			Choose an item.
Upper Ring	5	Are the Spring Plunger tips protruding from the Upper Ring by 0.13±0.03 inches?			Choose an item.
	6	Do the Separation Connector Pins (if attached) have visually uniform free pin heights (rev C only: and protrude past the profile of the Upper Housing)?			Choose an item.
	7	Does the Separation Switch plunger (if attached) compress and elongate 0.280±0.040 inches?			Choose an item.
	8	Is the accessible staking not delaminated?			Choose an item.
Lower Ring	9	Do the Separation Springs measure 2.1±0.1 inches in the elongated state?			Choose an item.
	10	Do the Separation Connector Pins (if attached) have visually uniform free pin heights?			Choose an item.
	11	Does the Separation Switch plunger (if attached) compress and elongate 0.280±0.040 inches?			Choose an item.
	12	Is the accessible staking not delaminated?			Choose an item.
Motor Bracket Assy.	13	Do the four Limit Switches change resistance more than 1.0 MΩ when depressed?			Choose an item.
Yield & Damage	14	Is the Lightband free of any yield or damage that prevents nominal operation?			Choose an item.

Table 20-1: Standard inspection of Lightband[33]

[33] Excerpted from PSC document 2001066C.

21. Lightband Testing and Procedures Performed by Customer

Customers often complete some of these tests and procedures after receiving the Lightband. Note: Lightband training is not optional. See Section 23.

Test or procedure	Objective	Remarks and cautions
Receive Lightband training from PSC	Learn how to operate Lightband and uncover unexpected potential integration difficulties	Can be performed with a PSC training Lightband or the customer's flight unit. Default location is PSC's facility.
Fit check to adjoining structures	Verify bolt patterns and clocking	Is the electrical wiring harness attached during this procedure?
Vehicle level vibration test	Verify workmanship and modes	Will the Lightband be overloaded at resonance? Are notching or force limiting methods employed?
Electrical initiation test	Verify the initiation circuit and power system from the launch vehicle will properly initiate the Lightband. Verify adjoining vehicle will receive the proper signal upon separation.	Ensure Lightband operation procedures are being followed by using the latest revision of PSC Document *2000781 MkII MLB Operating Procedure.*

Table 21-1: Testing and other procedures

Figure 21-1: Electro-mechanical fit check and a separation test with a Lightband

22. Ground Support Equipment (GSE)

Several pieces of GSE have been useful to customers in the past. In the cases noted in Table 22-1, PSC can supply production drawings. Generally, PSC neither supplies nor lends-out GSE.

Item	Description	Production drawings available to users?	Graphic
Mass mock-ups with the Lightband bolt pattern.	A structure that has the same mass and center of mass as the payload. Caution: structures such as these tend to exhibit low damping values and at resonance substantially increase response. Force limiting or notching of input may be required to prevent damage. Precise machining is required to meet flatness requirements.	NO	
Transition Ring (PSC Part Number 2000741)	Fastens to the Upper or Lower Ring. Useful to attenuate flatness issues of adjoining structures, allow access to fasteners to Lightband and to allow a Lightband to operate. The Lightband must be attached to an adjoining structure or it will flex too much when stowing.	YES	 
Vibration Adapter Plate	The interface between an electro-dynamic exciter and the Lightband or a Transition Ring.	YES	
Lightband Controller Components: oscilloscope, power supply, relay time, & ammeter	Used to stow, deploy, and set-for-flight the Lightband. Requires a cable between the Lightband and the controller with DB-9 connectors.	YES	

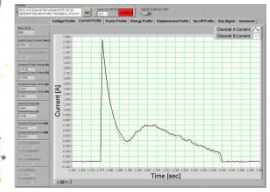
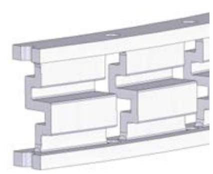
Item	Description	Production drawings available to users?	Graphic
Lightband Test Rack	PSC engineers use this in the field to automatically deploy, stow and set-for-flight the Lightband for high value programs. Records each motor's current and voltage at 5,000 samples/second. Calculates power, energy, and duration. Weighs 130 lb.	NO	 
Alignment pins	When blind mating is required, these pins add control to the mating process. Note: the Separation Springs already provide this function.	NO	
Lightband Compression Tool (PSC Part Number 4000637)	Overcome the Separation Spring force when the payload is integrated. This can substantially improve the available payload integration options.	NO (must be purchased)	
Lightband Stiffness Simulator	Emulates the stiffness of a Lightband	YES	 
Crane Compliance Sling (PSC Part Number 2002215)	Allows for axial compliance when mating the Upper and Lower Rings of the Lightband	YES	
Reduced head diameter fasteners	On the MLB 15.000-24 PSC has used ¼-28 socket head cap screws with the head diameter reduced to 0.340 in. This eliminates the interference fit described PSC Document 2000781.	YES	 

Table 22-1: Ground support equipment

23. Lightband Training

Lightband training for up to 8 users at PSC's facility is included in the price of the Lightband. Operation of the Lightband by any customer personnel is prohibited until he or she has received training. The training session lasts approximately 4-8 hours and can be performed at another location at an additional cost. Trained personnel are certified to operate their Lightband(s) for 24 months after successfully completing training.

Training sessions are incredibly important and reduce mission risk. In addition to learning how to operate the Lightband, customers will be able to discuss their expected integration scenario. PSC's trainers will help uncover potential unforeseen issues during integration and discuss all possible solutions. By having this discussion before customer operations and integration, customers will streamline all processes involving the Lightband and prevent expensive program delays.

At a minimum, the following topics will be covered during the training session

- How the Lightband works
- Best practices
- Warnings and warranty violation items
- Required materials
- Handling precautions
- Mechanical attachment procedure
- Stowing procedure
- Setting-for-flight procedure
- Deploying procedure
- Preparing the Lightband for compression
- Removal from adjoining structure procedure
- Horizontal integration procedure (if applicable)
- Lightband Compression Tool procedure (if applicable)
- Mission assurance verifications
- Customized discussion of mission integration details to improve efficiency
- Any other topics desired by the customer

24. Packing, Shipping and Unpacking Methods

PSC Document *2000827 MkII MLB Pack-Unpack Procedure* defines the methods to pack and unpack the Lightband from its shipping container.

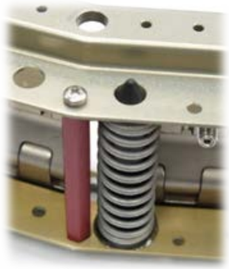
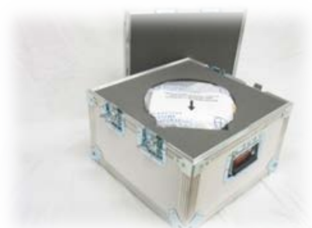
Graphic	Description
	The Lightband is shipped in the deployed state with the Motor Bracket Assembly in the stowed position to constrain motion during shipping. Red non-flight stand-offs are used to hold the Upper and Lower Ring separated.
	The Lightband is prepared for shipment. Typically, each Lightband is shipped in custom-designed protective case dedicated for that particular unit. The case is reusable.
	The Lightband is bagged and sealed.
	Composite foam shapes encapsulate the Lightband inside its case.
	The case is sealed with Lightband and documentation inside. The contents are indicated on the outside of the case.
FedEx®	The default shipping service is FedEx - Standard Overnight. Shipping weight and size varies by Lightband diameter.
	Customer receives Lightband and unpacks IAW with PSC Document *2000827 MkII MLB Pack-Unpack Procedure*

Table 24-1: Packing, shipping, and unpacking method

25. Procedures, Documents and Publications

Procedures and Documents
2000527 Procedure for Shield termination and Separation Connector installation to the Lightband
2000541 Lightband Stiffness
2000562 Thermal Resistance Test
2000715 Thermal Vacuum qualification of Motor Assembly
2000770 MLB FMEA
2000781 MkII MLB Operating Procedure
2000827 Procedure to Pack and Unpack Mark II MLB
2000849 MLB Materials and Surface Finish List
2000867 Lightband Retaining Ring Preload Recommendations
2001025 Separation Connector Data Sheet
2001066 MKII MLB Inspection Report
2001071 Spring Energy and its Variation
2001097 Line Load, Velocity, and Tip-off Calculator
2002159 Lightband Compression Tool Operating Procedure
2002204 Separation Switch Data Sheet
2002319 Lightband Loading Capability Proof Test
2002286 MkII MLB15.000-24 Analysis
2002305 MLB15.000-24 Shorted Motor TVAC Test Plan
2002319 Lightband Loading Capability Proof Test
2002653 Refurbishment Procedure
3000221 EMI Switch Shield Termination and Attachment Procedure
Reference Publications
Lightband As Enabling Technology AIAA-RS2 2004-7005
Multi-Payload Integration Lessons Learned from Space Test Program Mission 26, Proceedings from the 25th Small Sat Conference
SSC06-IX-7 Lessons Learned Developing Separation Systems For Small Satellites
Automating Separation System Testing, Proceedings of the 36th Aerospace Mechanisms Symposium, Glenn Research Center, May 15-17, 2002
Lessons Learned Designing A Spherical Satellite Release Mechanism, 39th Aerospace Mechanisms Symposium, Huntsville Alabama, May 2008
Criteria for Preloaded Bolts, NSTS 0837 Rev A, July 6 1998

Table 25-1: Procedures, Documents and Publications

26. Warranty

The Lightband warranty is defined in *PSC Document 1001015 Warranty MLB*.

27. Acknowledgements

PSC would like to thank Mike Froelich of Ball Aerospace and Greg Rahal of Orbital Sciences Corporation for their many constructive suggestions and patience with several of the anomalies PSC encountered as the Lightband attained its present maturity.

28. Glossary

- **ARO:** After receiving order
- **Bench-top testing:** A separation test of the Lightband on a bench top. Rate and velocity information are not recovered.
- **Build Complete Review (BCR):** Verify product assembly is complete (and hence ready for test). This includes bench-top separation.
- **CM**: Center of mass
- **CTE:** Coefficient of thermal expansion
- **Electro dynamic exciter (EDE):** A machine used to apply vibratory loading.
- **EMF**: Electromotive Force
- **End Item Data Package (EIDP)**: As run test plans, production log and certification.
- **Engineering development unit (EDU):** A Lightband designated for use on the ground to allow engineers to use flight like hardware. EDU are not exposed to standard testing, they only receive several bench-top separation tests prior to delivery
- **FEA**: Finite element analysis
- **Flight Unit:** A Lightband designated for use as a hardware that will fly into space. Flight units are exposed to standard testing prior to delivery
- **FMEA**: Failure modes and effects analysis
- **GSE:** Ground support equipment
- **IAW:** In accordance with
- **Lightband Compression Tool (LCT):** Assemblies used to safely mate the Upper and Lower Rings together.
- **MBA**: Motor Bracket Assembly
- **NBE**: Narrow bandwidth exceedance
- **Nominal Operation:** Separation of the Lightband at 23±10°C with both motors at 28±4 V.
- **Product Build Specification (PBS):** A summary document of requirements for testing and subsystem configuration (springs, switches, connectors).
- **SCC**: Stress corrosion cracking
- **Set-for-flight:** Moving the Ball Nut from the stow endplate to the deploy end plate. This relatively low power operation significantly decreases the time to initiate by reducing the distance the Ball Nut needs to travel to initiate.
- **SRS**: Shock response spectrum
- **Stow:** To join the Lightband by operating the motors until a stow Limit Switch opens a circuit
- **Test Readiness Review (TRR):** Verify test plans meet PBS
- **Time to initiate:** Power on until any deploy Limit Switches first opens a circuit
- **Time to deploy (or separate):** Power on until a loop-back in a Separation Connector opens a circuit. This corresponds to about 0.130 inches of travel in the X_{LB} direction.
- **Test Complete Review (TCR)**: After each test, the meeting that is held to review the results of the test. The outcome of the meeting is to deem the test a success or failure. At a minimum, two PSC engineers and either the Chief Engineer or President must attend.
- **TML**: Total mass loss
- **WRT**: With respect to